AMERICAN UNIVERSITY OF BEIRUT

ALTERNATIVE USES FOR BOARDS MANUFACTURED FROM RECYCLED PLASTIC BAGS IN CONSTRUCTION

by
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A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Engineering Management Program
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
January 2015

AMERICAN UNIVERSITY OF BEIRUT

ALTERNATIVE USES FOR BOARDS MANUFACTURED FROM RECYCLED PLASTIC BAGS IN CONSTRUCTION WITH SPECIAL FOCUS ON THE CASE OF LEBANON

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AMERICAN UNIVERSITY OF BEIRUT

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ACKNOWLEDGMENTS

First and foremost, I would like to thank Professor Walid Nasrallah for being my advisor for this master thesis and for providing me with his invaluable feedback and guidance. Prof. Nasrallah was always available to support my work through discussing my progress and planning the next steps.

I would like also to thank all of those who helped me to complete this work, especially Dr. Youssef Mouneimne , Prof. Ghassan Chehab, Prof. Issam Srour, members of the thesis committee, and Maher Salameh for their valuable and insightful comments.

AN ABSTRACT OF THE THESIS OF

Alamjad Hussain Salami for Master of Engineering
Major: Engineering Management

Title: Alternative Uses for Boards Manufactured from Recycled Plastic Bags in Construction

This thesis studies the uses of ECO-BOARD, a recycled plastic product. These uses are in the construction industry, where we consider the option of replacing several materials in the industry with ECO-BOARD. This is done by first administering specified tests on Eco-board. The second step is to establish specifications, through literature search, of material to be replaced by Eco-board. Then we administer a survey in order to acquire the cost of material to be replaced by Eco-board, in local markets. Then we estimate the cost of substituting Eco-board for each of the proposed material. At the end we recommended the best deployment for Eco-board within the construction industry.

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CHAPTER I

INTRODUCTION

Plastic bags have proven very difficult to deal with after consumers dispose of them. Recycling solutions have been devised but the processes these solutions entail are too expensive for wide-spread adoption, and hence not up to challenge of dealing with the growing problem of plastic bag littering. It is not only plastic bags that are not recycled but a lot of other plastic materials used in very high quantities on a daily basis which can be divided into two categories: flexible plastic and hard plastic. Food packages are the main flexible plastic and are identical to plastic bags (candy wrappers, ice cream packs, chocolate bars, potato chips bags, ground coffee bags). Hard plastics also used in large quantities are plastic cups, plastic plates, plastic cutlery, CD's, toothpaste tubes. Excluding these from the recycling process means settling for solving only a small part of the problem, while the larger part is left unsolved.

Cedar Environmental Co. (founded by Ziad Abichaker)have invented a technology to recycle all kinds of plastics that are rejected by mainstream recycling apparatus and transform them into thick plastic panel boards called ECO-BOARD used to replace wooden or steel boards in all kinds of technical/commercial applications. The pioneering aspect of this technology is its non-reliance on extrusion technology which is expensive and energy intensive. The process is easily duplicable and modular, so facilities can be set up to serve all communities large and small.

An innovative prototype production line of Eco-Boards has been operating over the past two years. The technology has been refined, expanding the usage of Eco-Board into many areas of applications. The Eco-board is comparable to the specs of wood and metal products when it comes to durability (plastic takes 500 years to degrade), functionality (used in the same way of wooden and steel boards) and sustainability (a typical Eco-Board uses about 3500 reclaimed plastic bags; Eco-Board is continuously recyclable, a broken Eco-Board can be shredded and remolded into a new Eco-Board).

This technology was put in place to divert all flexible & hard to recycle plastics from landfills. The main initial effort was to avert resorting to extrusion since it is a technologically expensive and energy intensive process, plus not all flexible plastics are easily extrudable (potato chips bags or ground coffee bags – these are laminated with aluminum foil). The manufacturing process creates no waste, as all trimmings from the boards can be shredded again, mixed with fresh plastic flakes from bags and molded again into panels.

This research effort revolves around the questions: Which material can Eco-board replace in the construction process? Which building systems and technologies (depending on geographical placements) can most economically benefit from the use of Eco-board? What policies might also prove decisive in incorporating Eco-board into this industry?

To answer the main question, best summed up as: "Where is Eco-board best deployed?" the work:

1. Administers specified tests on Eco-board.
2. Establish criteria for usability Eco-board of Eco-Board in the different systems
3. Administer a survey in order to acquire the cost of material to be replaced by Eco-board. (Local markets and abroad)
4. Estimate the cost of swap Eco-board with each of the proposed material.
5. Recommend the best deployment for Eco-board within the construction industry.

The rest of this thesis displays the problems of disposing of plastic bags and its effect on the environment, the construction material which compose partially or completely of recycled material, the methodology which we used to complete the goals set for this research, the results of tested administered on Eco-Board, the system replacement analysis and the conclusion and future work.

CHAPTER II

BACKGROUND LITERATURE SEARCH

A. Plastic Bags

Plastics are lightweight, strong, durable and cheap (Laist, 1987), rendering them suitable for the manufacturing of a wide range of products. These same properties happen to be the reasons why plastics are a serious hazard to the environment(Pruter, 1987; Laist, 1987).

Production of plastic has rapidly increased over the last 50 years. This increase in usage, especially disposable items of packaging, which make up 37% of all the plastic produced[1], has created waste management issues with end of life plastics accumulating in landfill and in natural habitats(Thompson, 2009).

Since the introduction of plastic carrier bags in the late 1970s, they have become a common aspect in today's life(Williams ID, 2004). For example the average annual consumption of plastic bags in the EU is estimated of 100 billion units(Facco, 2012)

These bags are commonly produced from high density polyethylene, a petroleum- derived polymer. They are usually used for carrying groceries, clothing and other merchandises. Although measures to reduce their usage have been implemented by an increasing number of municipalities and governments, plastic carriers are still used in large quantities. Due to their short usage life span, in 40% of the time under 1 month, a large waste stream is created. After their usage, plastic carrier bags are collected and disposed in landfills (Achilias, 2007; Barnes, 2009; Hopewell, 2009).However, even considering that a significant fraction of bags is improperly discarded, these lightweight bags are unintentionally transferred (i.e. wind-blown, rainfalls) away from landfill sites, losses in transportation and accidents (Barnes, 2009). Since they are also buoyant, an increasing load of plastic debris is being dispersed over long

[1] Web site: (PlasticsEurope, EuPC, EuPR and EPRO, 2009)

distances, and when they finally settle in sediments they may persist for centuries(Hansen, 1990; Goldberg, 1995; Goldberg, 1997; Ryan, 1987).

B. Problems with Extrusion

One of the recycling solutions for plastics is the process of extrusion or re-extrusion. Re-extrusion depends on reintroduction of scrap, industrial or single polymer plastic edges and parts to the extrusion cycle in order to produce products of similar material.(Al-Salem, Lettieri, & Baeyens, 2009)

One problem facing using Extrusion as a recycling solution is raw material storage. Raw materials for the extrusion process stored in low temperatures for long times require heating to room temperature before introducing it into the process. On the other hand raw materials stored at high temperatures lead to the consumption of polymer stabilization package thus leading to thermal degradation.(John R. Wagner Jr., 2014)

Also another problem caused by waste plastic as raw materials is the presence of foreign material. Problems caused by presence of foreign materials in the process are: Foreign objects in the feed throat prevent the screw from turning and also cause belt slippage. Also foreign material in the feed stream passes through the extruder, does not melt, and becomes trapped on the screen pack, preventing molten polymer from flowing through the screens to the die.(John R. Wagner Jr., 2014)

It is worth mentioning that the quality of extruded polymer is highly dependent upon the homogeneity of the molten polymer being fed into the die. (Vera-Sorroche, 2013) This also poses a problem of quality in case of presence of foreign objects.

Thus this process is only feasible with semi clean scrap, making it unpopular with recyclers.

In addition to the aforementioned polymer extrusion processes operate at poor efficiency. The polymer extrusion specific energy consumption decreases as processing speed increases.

Yet the melt flow thermal fluctuations increase as the speed of the process increases. Also polymer extrusion is an unpredictable process and is highly susceptible to fluctuations in nature. Also the process parameters are complexly coupled each to other which makes it difficult to set-up and control.(Chamil Abeykoon, 2014)

C. Problems with Gasification

Gasification, a process falling in the domain of thermolysis technologies, produces fuel or combustible gases from waste. There are several gasification technologies which can process plastic solid wastes, some of which are the WGT process, the Texaco Gasification process and the SVZ process. (Al-Salem, Lettieri, & Baeyens, 2009). However, in addition to requiring expensive equipment and infrastructure, the processes suffer from the problems such as tar and CO_2 emissions, as well as the problem if disposal of the ash formed. (Udomsirichakorn, Basu, Abdul-Salam, & Acharya, 2014)

D. Construction Material from Waste Products:

The limited capacity of landfills had pushed researchers to investigate the recycling of waste within the construction industry. The following material have been researched and found useable in the industry.

Concrete

One of the ways to solve the problem of waste concrete salvaged from demolition and construction sites is to use it as aggregates (Khalaf FM, 2004). Recycled concrete in the form of aggregate could also be a reliable substitute to using natural aggregates in concrete construction(Gilpin R., 2004).

Recycled concrete aggregate could be produced from (a) recycled precast elements and cubes after testing, and (b) demolished concrete buildings. Whereas in the former case, the aggregate could be relatively clean, with only the cement paste adhering to it, in the latter case the aggregate could be contaminated with salts, bricks and tiles, sand and dust, timber, plastics, cardboard and paper, and metals. It has been shown that contaminated aggregate after separation from other waste, and sieving, can be used as a substitute for natural coarse aggregates in concrete (Gokce A, 2004).

Recycled concrete can also be used as sub-base materials for roads: unbound material or cement treated granular material.(Molenaar AAA, 2002; Leite, Motta, Vasconcelos, & Bernucci, 2011; Vegas I., 2008; Xuan DX, 2010)

Glass

Wasted glass is readily incorporated as an alternative ceramic raw material or as a fluxing agent in stoneware, tiles, bricks, concrete blocks and “BituBlocks”(Brown, 1982; Manukyan, 1996; Lingart, 1998; Tucci, 2004; Rambaldi E. C., 2007; Topcu, 2004; Shayan, 2004; Zoorob S. E., 2006)

Wasted glass from PC monitors and TV sets are also deemed feasible in the manufacturing of clay bricks and roof tiles.(Dondi, 2009).

Clay Brick

Brick and tile manufacturing produces a large number of reject due to substandard product quality. This material is possibly used for landscaping when economically feasible, but could be recycled in concrete as aggregate where natural rock deposits are scarce. (Mansur MA, 1999; Mazumder, 2006)

Fly Ash

Fly ash resulting from incineration can be used as an ingredient to produce clay bricks(Chen Y, 2011; Chen Y, 2011; Lingling X, 2005; Chou, 2001; Kute, 2003; Lingling X, 2005). It is also well studied as a component of light weight concrete and BituBlocks bricks(Zoorob S. E., 2006).

Granite sawing wastes

The sawing wastes from Granite sawing mills could be used as an additive in the production of clay brick (Menezes, 2005).

Solid waste incineration plant slag

The slag of municipal solid waste incineration plants has been researched to be used as a partial replacement of clay in clay bricks. It has also been researched to be used in concrete brick-sand BituBlock(Lin, 2006; Zoorob S. E., 2006)

Tea

Used processed tea has been tested as an ingredient in clay bricks and proven to be feasible(Demir, 2008)

Cotton Waste

Wasted cotton from clothing industries could be used in the production of light weight concrete blocks (Algin, H., Turgut, P., 2008)

Rubber

Crumbs of waste rubber are viable as a partial replacement of aggregates in concrete blocks (Turgut, P., Yesilata, B., 2008)

Plastic

Pellets of recycled plastics (LDPE) are used as partial aggregate replacement in asphaltic concrete. (Zoorob S. S., 2000)

Steel Slag

Steel slag has been researched to be used in BituBlocks as a partial replacement of aggregate.(Zoorob S. E., 2006)

E. Common Criteria

The usual aspects studied by researchers when introducing the use of a recycled element into the production of a building material are physical, mechanical, chemical and economical.

The physical properties usually tested are porosity, water absorption, density and bulk density.(Loryuenyong, 2009; Eguchi, 2007; Pinto, 2012)

The mechanical properties usually investigated are the heat capacitance, thermal conductivity, compressive strength, tensile strength and elastic modulus(Eguchi, 2007; Pinto, 2012; Poon, 2007)

The chemical properties usually tested for are fire resistance and bond property(Eguchi, 2007).

The economic aspects investigated in literature (Limbachiya, 2000; Bektas, 2009; Mickovski, 2013; Knoeria, 2011; Eguchi, 2007; Pinto, 2012)include:

- Durability,
- The difference in cost between using recycled and fresh material,
- Public and private sector policy effect.

CHAPTER III

METHODOLOGY

In order to achieve a comprehensive understanding of the Eco-board we first of all administered a number of tests to determine its physical, mechanical and chemical properties.

The physical property we investigated is the water absorption. This was done by applying the ASTM D570 standard test. This standard of tests determines the relative absorption of a plastic specimen allowing us to determine the suitability of use of the Eco-board in humid and water-suspect environments.

The mechanical properties we tested for are the following:

1. Heat capacity, which is determined through applying the ASTM E1269 standard using calorimetric measurement device.
2. Thermal conductivity, which is determined through applying the ASTM E1530 standard using hot-plate/cold-plate box.
3. Both properties are used to determine the thermal resistance of the Eco-board, which in turn is used to determine the insulation level.
4. Bending strength, which are determined using the ASTM D2344/D2344M standard for rigid plastics: This is done by loading the specimen in a three point bending configuration.
5. Tensile strength and modulus of elasticity, which are determined using the ASTM D638-10 standard. This is done using a dumbbell shaped specimen tested under specific conditions of pretreatment and testing machine speeds.
6. The tensile and bending strength and modulus of elasticity properties allow us to estimate the load conditions which can be applied to the Eco-board.
7. As for the chemical properties we tested for fire resistance properties, which was determined through applying the ASTM E84 standard: this is in turn done through exposing

the surface of the specimen to specific fire conditions in order to measure the surface flame spread and smoke density.

8. We also tested for the chemicals emitted in case of overheating or fire through using an Atomic Absorption Spectrophotometer.

In order to determine suitable applications of Eco-board in the building process we adopted a two dimensional approach. The first dimension is determining the aforementioned physical, mechanical and chemical properties through tests which we administered and compared these properties to those of a specified group of material in the building process, within the criteria of usability in the systems.

The second dimension is to acquire the costs of using the material in the aforementioned group and compare to the costs of replacing each one with Eco-board. The costs of replacing the material with Eco-board include in addition to the direct costs, the estimated costs of possible redesign of structure, difference in life time and special additional modifications on the Eco-board.

The list of materials which Eco-board can replace includes: Oriented strand boards, plywood used for concrete framework and finishing phases, gypsum boards used as walls and false ceilings, window frames, brick tiles on roofs, and different configurations in the external wall systems.

CHAPTER IV

EXPERIMENTAL RESULTS

A. Absorption

This test was administered at the Central Research Science Laboratory (CRSL) at AUB.

- ***Standard***

For the purpose of testing for the absorption of Eco-Board the compatible ASTM Standard was found to be ASTM D570.

- ***Specimens***

  - ***Dimensions***

The test specimen for sheets was in the form of a bar 76.2 mm (3 in.) long by 25.4 mm (1 in.) wide by the thickness of the material.

  - ***Number of Specimens***

It is required to test at least three specimens.

- ***Procedure***

  - Put the specimens in an oven at 200^{o}C temperature for a minimum of 1 hour in order to remove any preexisting moisture in the material.
  - Weight the specimens after removing from the oven.
  - Immerse the specimen in water completely for 24 hours.
  - After removing specimen from water weight it again.

- ***Results***

  - ***Absorption by Weight for Eco-Board in Factory Conditions***

%weight increase= $\frac{Wa-Wb}{Wb} * 100$

Where W_b is weight before immersion, and W_a is weight after 24 hours of immersion.

The result was 8.34% increase in weight

- ***Absorption by Weight for Edge-Sealed Eco-Board***

The Samples were sealed at the edges by applying a layer of polyurethane-based water sealant.

The result of the test after edge-sealing was found to be 0.02% increase by weight.

B. Burn Rate

This test was administered at the Industrial Research Institute located at Lebanese University Campus at Hadath.

- ***Standard***

In order to determine the burning behavior of Eco-Board the compatible ASTM Standard was found to ASTM E84.

- ***Specimens***

  - ***Dimensions***

The standard dictates that the dimensions are to be compatible to the fire chamber in use, which in our case was 10 cm wide and 20cm long. The thickness of the specimen should be that of the board, which was 2 cm in our case.

- ***Procedure***

After Igniting the gas burner we have to observe and record the maximum distance covered by the flame and record the time. The test is to be continued for a period of 10 minutes. It is allowed to stop the test prior to that if the specimen is totally consumed.

- ***Results***

  - ***Flammability***

It was found that the specimen is flammable and drips upon exposure to fire, also it emits a thick cloud of smoke.

- ***Burn Rate***

The flame traveled at an average rate of 4 cm/min. According to the lab administrator comparatively this rate is a slow one.

C. Specific Heat

The specific heat of eco-board was tested for at the AUB CRSL.

- ***Standard***

In order to test for the specific heat of Eco-Board the compatible ASTM Standard was found to be ASTM E1269.

- ***Procedure***

The analyzer usually consists of a high-precision balance with a pan (generally platinum) loaded with the sample. The pan is placed in a small electrically heated oven with a thermocouple (temperature sensor) to accurately measure the temperature. The atmosphere may be purged with an inert gases to prevent oxidation or other undesired reactions.

Heat the test chamber, and the specimen, at rate of 20^{o}C/min. Keep heating, and recording the heat graph, of the specimen at this rate until a steady base line is achieved. After steady state stop heating.

- ***Results***

The heat capacity to reach steady state was found to be 16.5 J/g ^{o}C, or 16500 J/Kg K

D. Gaseous Emissions

The gaseous emissions of eco-board were tested for at the AUB CRSL.

- ***Apparatus***

Using the TGA-FTIR Technique, we were able to determine the emitted gas when Eco-Board at various temperatures starting from room temperature to the point of its disintegration at 730^{o}C.

- ***Results***

  - ***Emitted Gas***

The spectrophotometer was able to identify the emitted gas as Cyclohexane, 1-dodecyl-4-octyl-, or C26H52. This was done by comparing the wave number vs. Absorbance units of the emitted gases to those already established in the machine's database. The flash point of Cyclohexane, 1-dodecyl-4-octyl- is 214.857 °C, while its boiling point is 445^{o}C.

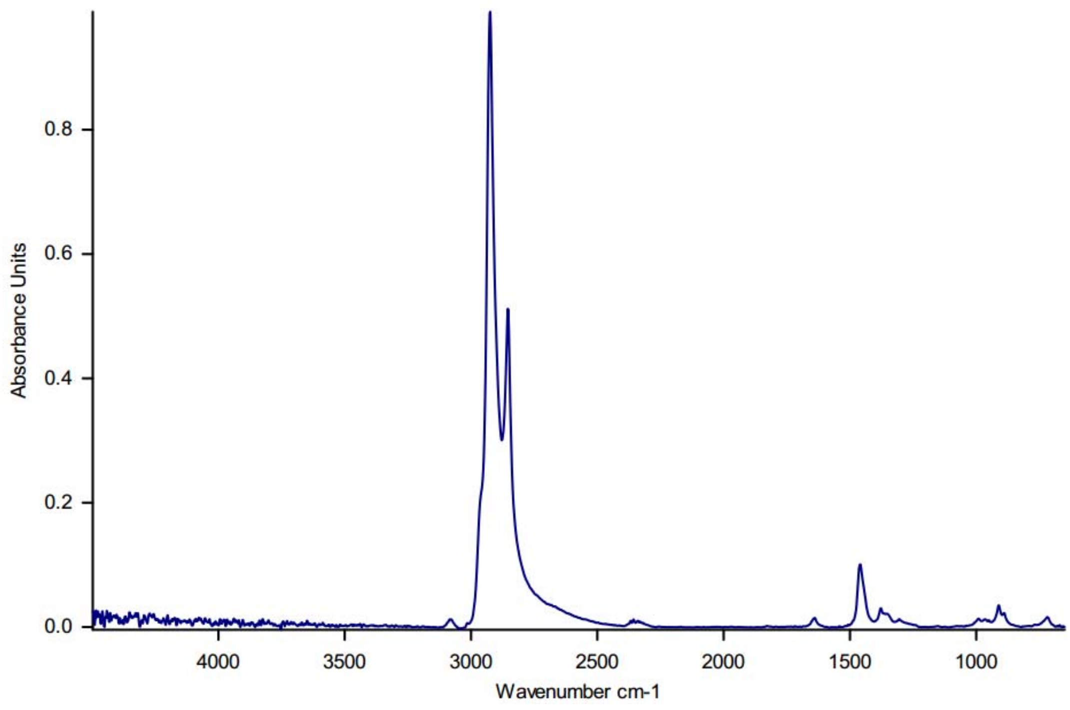


Figure 1: Gas Emission

Also we were able to establish the temperature at which the gas starts being emitted, which is approximately 300^{o}C.

It is worth noting that the TGA-FTIR machine has the following shortcomings:

- If might miss on reporting a gas if it is found in small traces in the tested material.
- The machine's detection of certain gases could be is limited to gasses available in the database.
- It cannot detect which material is lost at which temperature.

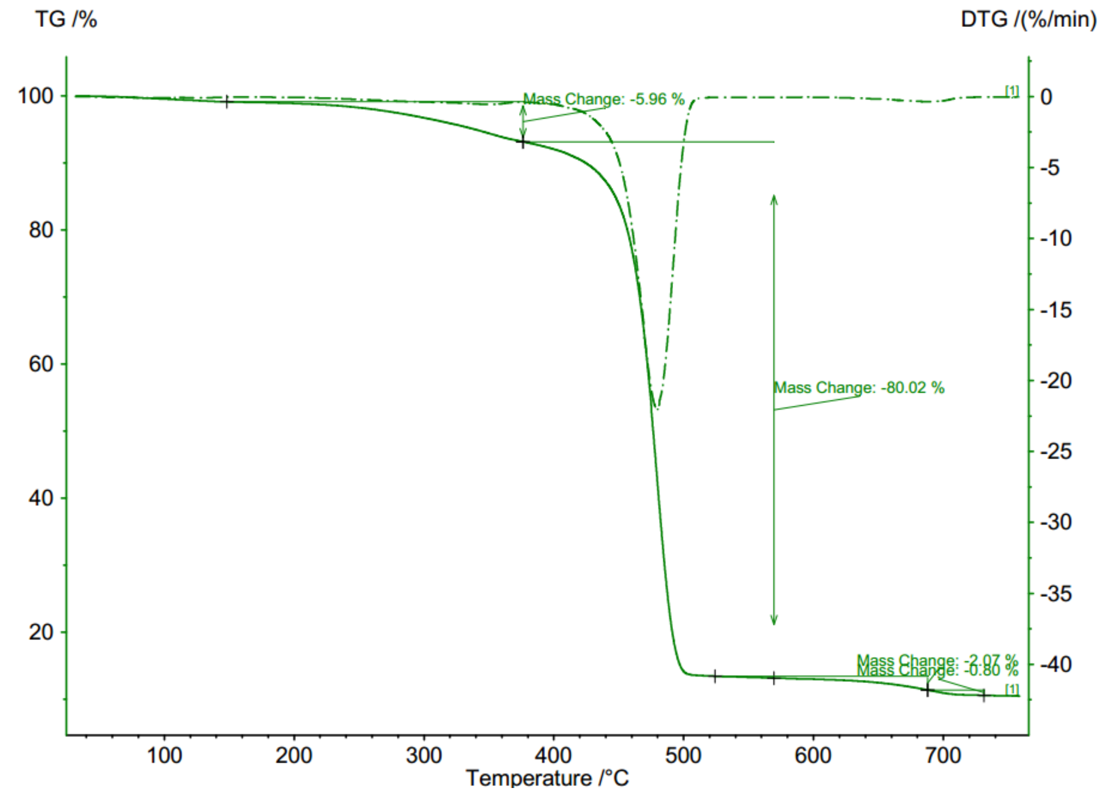


Figure 2: Mass Change vs. Temperature

This figure shows two plots. The first is the solid curve which conveys the percentage decrease in mass of Eco-board as temperature changes. In our case the mass decrease started at 300^{o}C and stops at 730^{o}C. The second, which is the dotted curve, is the first derivative of weight loss curve and it is %mass lost per minute. The peak of the first derivative indicates the point of greatest rate of change on the weight loss curve. This is also known as the inflection point, which happens to be at 480 ^{o}C in our case and has a -22.5% change/min.

E. Thermal Conductivity

The thermal conductivity of Eco-board was tested at the AUB Heat Transfer lab

- ***Standard***

For the purpose of testing for the thermal conductivity of Eco-board the compatible ASTM Standard was found to be ASTM E1530.

- ***Specimens***

    - ***Dimensions***

The dimensions of the specimen are to be compatible with the machine size. The one available at AUB Heat Transfer Lab requires a sample 30-30-0.5 cm

- ***Procedure***

The test procedure is to heat up the specimen until it reaches steady state condition. The time it requires to reach steady state is the indicator of its thermal resistance

- ***Results***

    - ***Thermal Conductivity***

The thermal resistance was found to be 0.016 m^2K/W for a specimen of 5 mm thickness. This means that the thermal conductivity of Eco-Board was found to be 0.309 W/m-K

F. Bending Strength

The bending properties were tested at the AUB materials lab.

- ***Standard***

For the purpose of testing for the bending properties of Eco-Board the compatible ASTM Standard was found to compatible ASTM D2344/D2344M.

- ***Specimens***

  - ***Dimensions***

"For materials 2.0 mm or greater in thickness (which is the case of Eco-board) the depth of the specimen shall be the thickness of the material. For all tests, the support span shall be 4 (tolerance ±1) times the depth of the beam. Specimen width shall not exceed one fourth of the support span for specimens greater than 3.2 mm (1⁄8 in.) in depth. Specimens 3.2 mm or less in depth shall be 12.7 mm (1⁄2 in.) in width. The specimen shall be long enough to allow for overhanging on each end of at least 10 % of the support span, but in no case less than 6.4 mm (1⁄4 in.) on each end. Overhang shall be sufficient to prevent the specimen from slipping through the supports."

Thus we chose to use a specimen 20mm thick (standard Eco-Board thickness), 140 mm long and 16 mm wide.

  - ***Number of Specimens***

It is required to have at least five specimens but recommended to have ten. Thus we performed the test on 10 different specimens.

- ***Procedure***

The machine is operated at a recommended testing speed is 4 mm/min until failure occurs.

- ***Results***

  - ***Bending Strength***

The output of this test was the force applied versus the strain associated with it. We were able to calculate the Stress (Pa) using the following equation

$$\sigma = \frac{0.75F}{A}$$

Where σ is the Stress, F is the applied force and A is the cross-sectional area of the specimen.

The Figures below are of two specimens, relaying Stress vs. Elongation

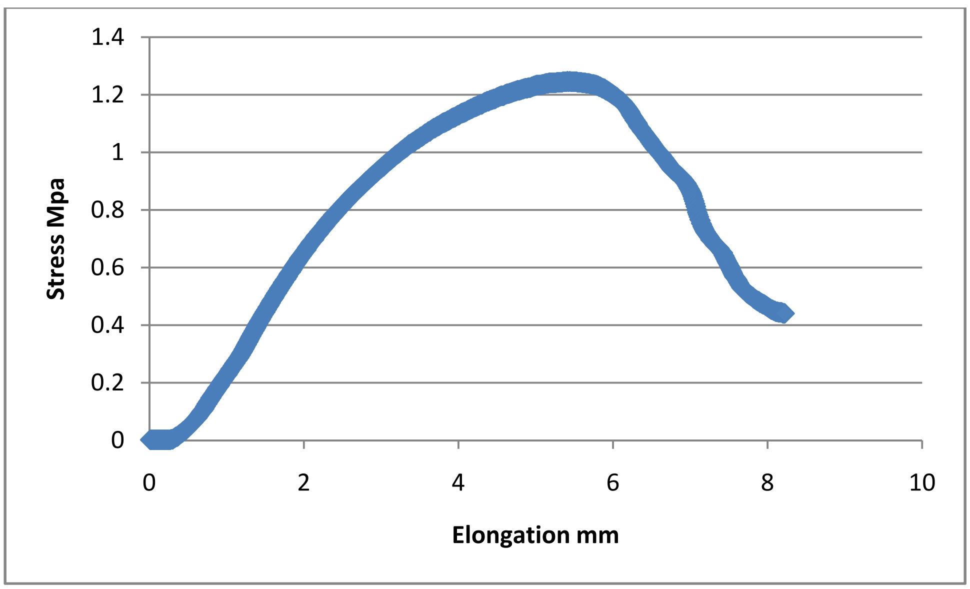


Figure 3: Stress (MPa) vs. Elongation (mm)

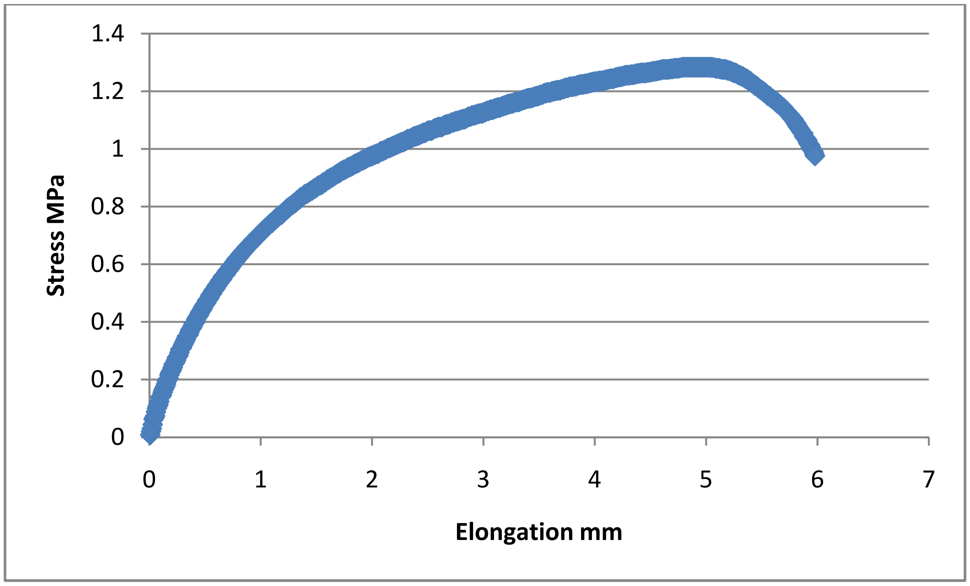


Figure 4: Stress (MPa) vs. Elongation (mm)

Since Eco-Board is not homogeneous, we needed to use the Weibull distribution to determine the Bending strength of the material.

The formula of the probability density function of the general Weibull distribution is

$f(x)=\gamma/\alpha(((x-\mu)/\alpha)^\wedge(\gamma-1))\exp(-((x-\mu)/\alpha)^\wedge\gamma)\ x\geq\mu;\gamma,\alpha>0$

where *γ* is the shape parameter, *μ* is the location parameter and *α* is the scale parameter.

Using the results from our ten specimens we generated a cumulative Weibull chart using f(x)= 1-R(x). "f(x)" represents the probability that the failure strength is equal to or less than "x". The reliability R(x), which is "$\exp((x-x_0)/\alpha)^\wedge\gamma$", represents the probability that the failure strength is at least "x". The Weibull CDF x_0 is called minimum life. When $x=x_0+\alpha$ then $f(x_0+\alpha)=1-(1/e)=0.6322$ which is the characteristic life, which means that there is 36.7% of the tested specimen of the failure strength α. Thus we determined the stress at the 63%.

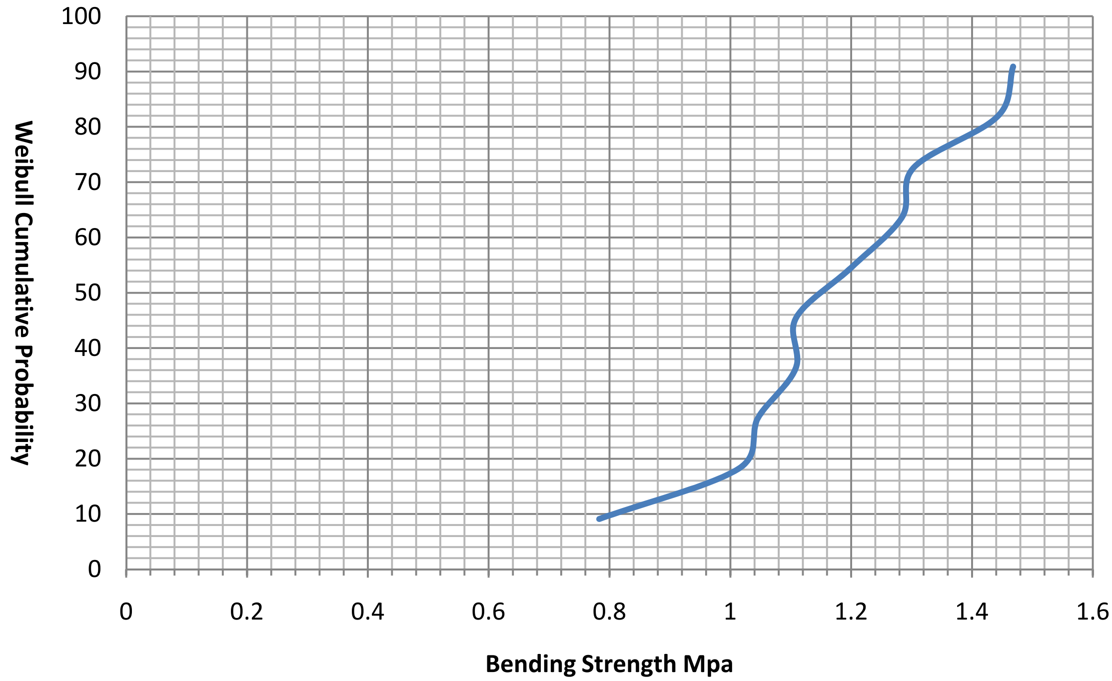


Figure 5: Weibull Cumulative Distribution of Bending Strength

The bending strength is 1.28 MPa.

G. Tensile and Shear Strength

The tensile properties were tested at the AUB materials lab.

- ***Standard***

For the purpose of testing for tensile properties of Eco-Board the compatible ASTM Standard was found to be ASTM D638-10 standard.

- ***Specimens***

    - ***Dimensions***

The following was to identify fabrication parameters of the specimens in accordance with the following schematics for the strength test:

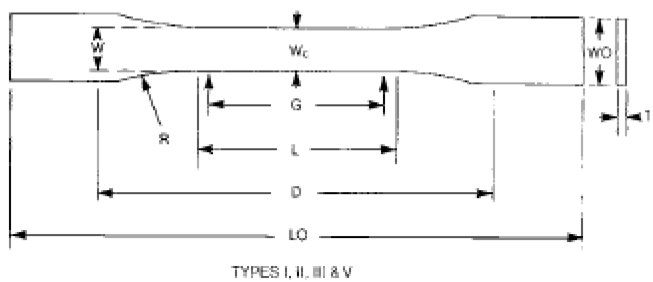


Figure 6: Specimen for ASTM D638-10

Type III was identified as the most compatible to the material. Type III allows up to 14.55 mm of thickness which is within the board's thickness. In accordance with Type III we had to change the overall length of the specimen to 246 mm and the maximum width 19mm and minimum of 6 mm.

- ***Number of Specimens***

It is required to test at least five specimens but recommended to test ten. Thus we performed the test on 10 different specimens.

- ***Procedure***

The machine is operated at a recommended testing speed is 5 mm/min until failure occurs.

- ***Results***

  - ***Tensile Strength***

The output of this test was the force applied versus the strain associated with it. We were able to calculate the Stress (Pa) using the following equation

$$\sigma = \frac{F}{A}$$

Where σ is the Stress, F is the applied force and A is the cross-sectional area of the specimen.

The Figures below are of two specimens, relaying Stress vs. Elongation

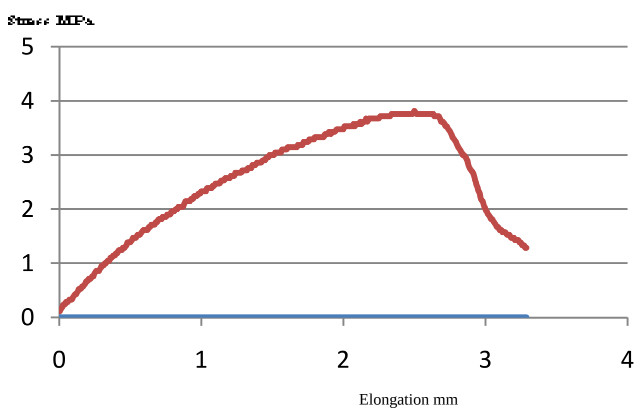


Figure 7: Stress (MPa) vs. Elongation (mm)

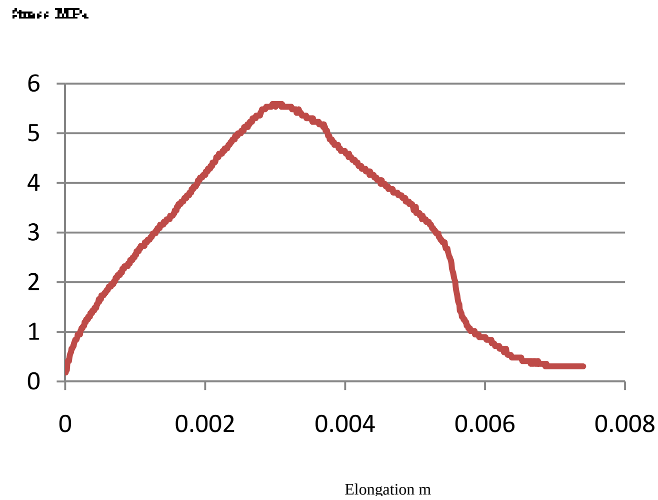


Figure 8: Stress (MPa) vs. Elongation (mm)

Since Eco-Board is not homogeneous, we needed to use the Weibull distribution to determine the Tensile strength of the material.

Using the results from our ten specimens we generated a cumulative Weibull chart and determined the stress at the 63%.

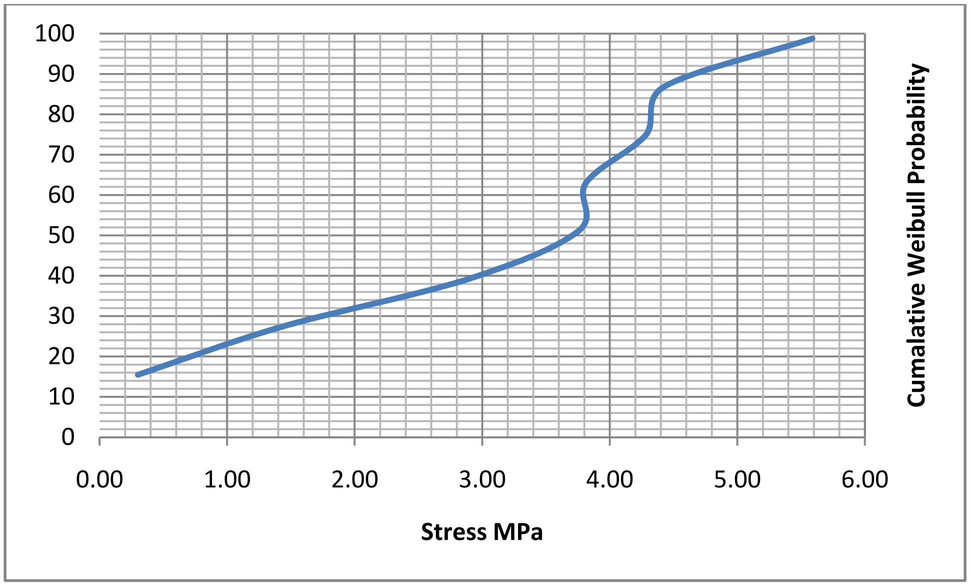


Figure 9: Weibull Cumulative Distribution of Tensile Strength

The tensile strength is 3.814 MPa.

Using the Tresca's criterion which states that when Yielding occurs in any material, the maximum shear stress at the point of failure equals or exceeds the maximum shear stress when yielding occurs in the tension test specimen.

Thus $\sigma_{sy}=0.5\ \sigma_t$ where σ_{sy} is the shear strength and σ_t is the tensile strength. This means that the shear strength of Eco-board is 1.907 MPa.

- ***Modulus of Elasticity***

The modulus of Elasticity is calculated using the following formula:

$E_1=\frac{\sigma 1}{\varepsilon 1}$ for the elastic portion of the stress-strain diagram and $E_2=\frac{\sigma 2}{\varepsilon 2-\varepsilon 2}$

Where E is the modulus of elasticity, σ is the stress and $\varepsilon=\frac{l1-l0}{l0}$ is the unitless strain.

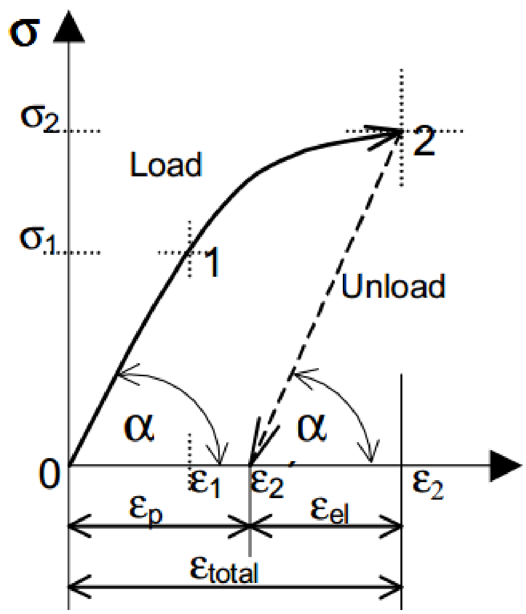


Figure 10: Modulus of Elasticity for Materials with Elastic and Plastic Behavior

Again using Weibull distribution we found out the Modulus of elasticity to be 208 MPa at 63% cumulative probability.

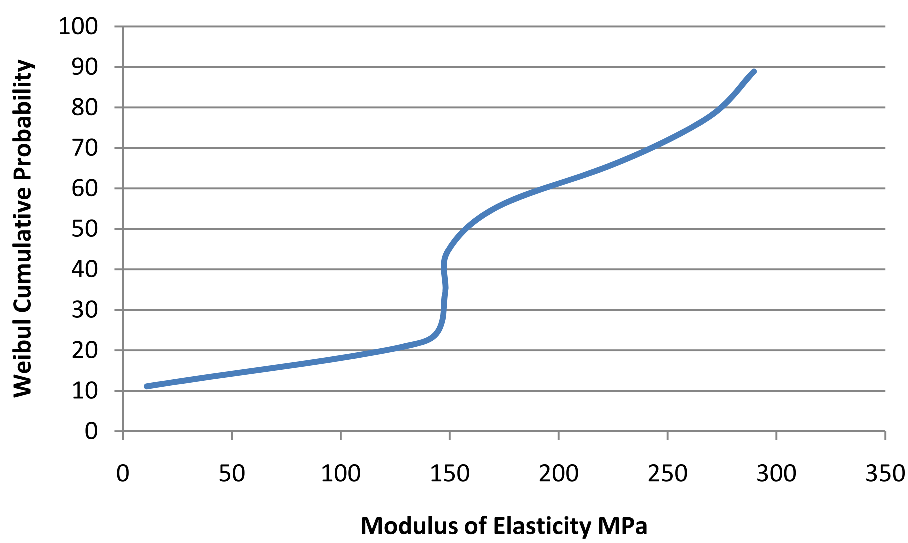


Figure 11: Weibull Cumulative Distribution of Modulus of Elasticity

The tables below convey the mechanical properties of Plywood and OSB:

Stress Grade	Stress Value MPa					
	Bending F_b	Tension F_t	Shear F_s	Compression F_c	Modulus of Elasticity E	Modulus of Rigidity G
F11	11.0	6.6	1.80	8.3	10500	525
F14	14.0	8.4	2.05	10.5	12000	625
F17	17.0	10.2	2.30	12.8	14000	700
F22	22.0	13.2	2.30	16.5	16000	800
F27	27.5	16.5	2.30	20.6	18500	925

Table 1: Mechanical Properties of Plywood(Lyngcoln, 1993)

The Grades F11 through F27 is a representation of the maximum bending strength of the board. This grade is identified by the supplier.

Layer	Strand orientation	Density		Strength	
		Mean	SD[a]	Mean	COV
		---- (pcf) ----		-- (psi) ----	
1	Perpendicular	52.5	2.50	616	0.37
2	Perpendicular	49.1	1.71	522	0.47
3	Perpendicular	44.7	1.63	384	0.41
4	Parallel	40.3	1.28	616	0.61
5	Parallel	37.4	0.69	699	0.41
6	Parallel	36.1	0.37	576	0.33
7	Parallel	35.2	0.32	495	0.34
8	Parallel	34.7	0.33	446	0.27
9	Parallel	34.8	0.29	594	0.42
10	Parallel	35.5	0.46	546	0.22
11	Parallel	36.9	0.64	672	0.33
12	Parallel	39.1	0.85	615	0.59
13	Perpendicular	42.5	1.45	484	0.39
14	Perpendicular	46.7	1.58	466	0.26
15	Perpendicular	50.2	1.16	634	0.41
Average		41.0	1.02	558	0.39

Table 2: Tensile Strength of OSB by Layer Number(STEIDL, 2003)

Layer	Strand orientation	Density		Strength		MOE	
		Mean	SD[a]	Mean	COV	Mean	COV
		---- (pcf) ----		---------- (psi) ----------			
1	Perpendicular	52.4	2.25	860	0.46	1.98E + 05	0.37
2	Perpendicular	49.0	1.61	1013	0.32	1.53E + 05	0.22
3	Perpendicular	44.7	1.57	893	0.36	1.44E + 05	0.38
4	Parallel	40.2	1.17	1129	0.43	2.29E + 05	0.43
5	Parallel	37.4	0.66	1106	0.33	2.27E + 05	0.24
6	Parallel	36.0	0.36	895	0.38	2.08E + 05	0.34
7	Parallel	35.2	0.32	849	0.36	1.83E + 05	0.30
8	Parallel	34.7	0.33	764	0.36	1.93E + 05	0.30
9	Parallel	34.8	0.29	906	0.40	2.08E + 05	0.26
10	Parallel	35.4	0.47	1127	0.41	2.48E + 05	0.41
11	Parallel	36.9	0.62	983	0.32	2.20E + 05	0.27
12	Parallel	39.1	0.84	837	0.40	1.65E + 05	0.38
13	Perpendicular	42.5	1.49	923	0.50	1.40E + 05	0.38
14	Perpendicular	46.7	1.52	922	0.29	1.53E + 05	0.24
15	Perpendicular	50.3	1.09	1024	0.50	1.64E + 05	0.39
Average		41.0	0.97	949	0.39	1.89E + 05	0.33

Table 3: Bending Strength of OSB by Layer Number(STEIDL, 2003)

CHAPTER V

CRITERIA AND ANALYSIS

A. Roofing Material for Mild Weather Shelter

A mild weather shelter is a roofing system for open spaces which is usually composed of support steel structure and a light gauge steel roof. We do not intend to alter the structures supporting the roof so we did not consider the loads which they are designed upon. The only consideration would be the loads which directly affect the Roofing (steel or Eco-board), thus the only load which we considered was the snow load, which is estimated at a maximum of 57 KPa. This load is less than both the tensile and bending strength of Eco-board, which stand at 3.8 and 1.28 MPa consecutively.

This means that Eco-board can act as a roofing material for the mild weather shelter. The only problem which might arise stems from the absorption rate by weight of Eco-Board, which is 8.3%. This is due to the fact that Eco-Board is multilayered, as polyethylene in itself has a water absorption <0.1%(Peacock, 2000). This could be solved by insulating the edges of Eco-board, which are the areas of water absorption (since water enters in between layers from the edges), using polyurethane based water insulation products.

The cost $/m^2 of ceiling area (not roofing area) was calculated for each of two options: a light gauge steel roof and an Eco-Board roof.

For the eco-board we accounted for, in addition to the cost of the board, the cost of coloring the board, which was done using a two layer rubber paint.

The cost of 1 m^2 of light gauge steel roofing is 30.6 $. The steel structure for a fully functional floor stands at 160 $/m^2. Thus the total cost is 190.6$/m^2.

A single pane Eco-board costs 24.6 $/m^2$. To calculate the total cost we have to add the costs of insulation and painting, which stand at 1.09$/m^2$ and 1.82 $/m^2$ respectively. The total cost is 187.5 $/m2.

Recommendations

Table 4: Comparison of Steel Roofing and Eco-Board Roofing

Configuration	*Cost $/m²*
Light Steel Gauge Roofing	190.6
Eco-Board Roofing	187.5

Using Eco-Board is better for this system, as it costs 3.1$/m^2$ less than using light gauge steel as a roofing material.

B. Partition Walls and False Ceilings

- ***Partition Walls***

The partition walls system is usually made of gypsum boards. The boards are supported by a light-gauge steel or aluminum structure. Eco-board replaces the gypsum board only. Thus the differences is related to the boards only not to the structure steel. The standard load bearing steel stud for a partition wall forces a 60 cm gap between the two walls.

For this use eco-board has to be painted and has to be treated for fire proofing, which is done by painting it with a special fire proof lacquer layer. This also applies for gypsum board. Both were accounted for.

The comparison was set on the base of the cost of the boards of one face of the wall and half of the gap space in $/m^2 of wall.

The thermal conductivity of Gypsum is K_G=0.15 W/m^{2}K , that of fiber glass K_F=0.031 W/m^{2}K, that of rock wool K_R=0.033 W/m^{2}K and that of Eco-Board is K_E=0.307 W/m^{2}K. The thermal conductivity of the aforementioned double Eco-Board K_{dE}=0.04 W/m^{2}K

- ***Gypsum***

  - ***Fiber Glass Insulation***

We considered a fire graded gypsum board. This board costs 6.25 $/m^2 at its natural color. The painting of the board costs 1$/m^2. Using 30 cm thickness (half of the gap, the other half is calculated with the other side of the wall) of Fiber glass (density 32 Kg/m^3) as insulation costs 42 $/m^2. The total cost of using gypsum board, with fiber glass insulation, as partition walls is 49.25 $/m^2.

The thermal conductivity of this configuration is that of Gypsum board , which is 0.15 W/m^{2}K(Huanzhi Zhang, 2012), and of the fiber glass, which using the lumped capacity would end up as K_{GF}=0.025 W/m^{2}K.

  - ***Rock Wool Insulation***

The board costs 6.25 $\$/m^2$ at its natural color. The painting of the board costs 1$\$/m^2$. Using 30 cm thickness of Rock Wool (density 40 Kg/m^3) as insulation costs 27 $\$/m^2$. The total cost of using gypsum board, with fiber glass insulation, as partition walls is 34.25 $\$/m^2$.

The thermal conductivity of this configuration is K_{GR}=0.027 W/m^2K.

- ***Eco-Board***

  - ***Single Board***

Using a single pane Eco-board costs in addition to the cost of Eco-board the costs of painting and fireproofing. The cost of painting being 1.82 $\$/m^2$ and the cost of fireproofing being 2 $\$/m^2$, the total cost of using a single pane Eco-board is 28.82 $\$/m^2$.

The thermal conductivity of this configuration is that of the Eco-board and 30 cm of air which is 0.023 $W.m^2K$

  - ***Double Board***

Using the double pane Eco-Board (with a Styrofoam board in between) costs 61.1 $\$/m^2$.

This configuration has a thermal conductivity of 0.015 W/m^2K.

- ***False Ceilings***

Suspended ceiling systems are made up of support structures and gypsum boards. The support system is the same for Eco-Board, thus we only considered the differences between the boards. We intend to use both one panel Eco-board and two panel Eco-board.

We compared the cost in $\$/m^2$ of ceiling area. This included the costs of painting and fireproofing eco-board and fireproofing of gypsum boards.

It is worth mentioning that Eco-Board can be used only in wall to wall suspended ceiling cases. This is because any other form of suspended ceiling requires either molding of Eco-board, which is not available at the moment, or using a CNC machine thus rendering it too expensive to use.

- ***Gypsum***

  - ***Single Board***

We considered a gypsum board covered with a layer of fire graded PVC. This board costs 8.25 $\$/m^2$.

The thermal conductivity of this configuration is 0.15 W/m^2K

  - ***Single Board& Styrofoam Insulation***

The Gypsum Board costs 8.25 $\$/m^2$. The 5 cm thick Styrofoam board costs 7.25 $\$/m^2$. The thermal conductivity of this configuration is 0.0375 W/m^2K and costs 15.5 $\$/m^2$.

- ***Eco-Board***

  - ***Single Board***

Using a single pane Eco-board costs in addition to the cost of Eco-board the costs of painting and fireproofing. The cost of painting being 1.82 $\$/m^2$ and the cost of fireproofing being 2 $\$/m^2$, the total cost of using a single pane Eco-board is 28.82 $\$/m^2$.

The thermal conductivity of this configuration is 0.307 $W.m^2K$

  - ***Double Board***

Using the double pane Eco-Board (with a Styrofoam board in between) costs 61.1 $\$/m^2$.

This configuration has a thermal conductivity of 0.04 W/m^2K.

- ***Recommendations***

Table 5: Comparison of Partition Wall and False Ceiling System

Configuration	***Cost $/m²***	***Thermal Conductivity W/m²K***
Partition Walls		
Gypsum Board &Fiber Glass Insulation	49.25	0.025
Gypsum Board &Rock Wool Insulation	34.25	0.027
Single Eco-Board	28.82	0.023
Double Eco-board	61.1	0.015
False Ceiling		
Single Gypsum Board-Covered with PVC	8.25	0.15
Single Gypsum Board-Covered with PVC	15.5	0.0375
Single Eco-Board	28.82	0.307
Double Eco-Board	61.1	0.04

For the partition walls it is recommended to use a single Eco-Board as the difference in thermal conductivity of the compared configurations is negligible and the single Eco-board has the lowest cost.

As for the false ceilings, the recommendation was based on whether high level of thermal insulation is priority. In this case Eco-Board is not considered viable, as its thermal insulation is lower than gypsum and it is still considerably costlier.

C. Window Frames

- ***DESIGN CRITERIA FOR FRAME***

  - ***Fasteners, Sealants and Gaskets:***

The fastener system is a light steel skeleton for the window frame. We proposed to use the same method of fastening for Eco-Board windows. The sealant and gasket design should be consistent with industry standards. The gasket should be continuous around the perimeter of the glass pane and its stiffness should be at least 68.9 MPa. We proposed to use the same gaskets used in PVC windows, thus we did not account for the costs of replacing them for Eco-Board windows.

  - ***Frame Loads:***

Frame deflections induce higher principal tensile stresses in the pane, thus reducing the strain energy capacity available.

In addition to the load transferred to the frame by the glass, frame members must also resist a uniform line load, r_u, applied to all exposed members. Until criteria are developed to account for the interaction of the frame and glass panes, the frame and fasteners should satisfy the following design criteria:

- Stress: The maximum stress in any member should not exceed $F_y/1.65$, where F_y = yield stress of the members material.
- Fasteners: The maximum stress in any fastener should not exceed F_y / 2 .00.

The design loads for the glazing are based on large deflection theory, but the resulting transferred design loads for the frame are based on an approximate solution of small deflection theory for laterally loaded plates. Analysis indicates this approach to be considerably simpler and more conservative than using the frame loading based exclusively on large deflection membrane behavior, characteristic of window panes. According to the assumed plate theory, the design load, r_u, produces a line shear, V_x, applied by the long side, a, of the pane equal to:

$V_x = C_x\, r_u\, b \sin(\pi x / a)$ (1)

The design load, r_u, produces a line shear, V_y, applied by the short y side, b, of the pane equal to:

$V_y = C_y \ r_u \ b\,sin(\pi y/b)$ (2)

The design load, r_u, produces a corner concentrated load, R, tending to uplift the corners of the window pane equal to:

$R = -C_R \ r_u \ b^2$ (3)

The table below presents the design coefficients, C_x, C_y, and C for practical aspect ratios of the window pane. The loads given by Equations 1, 2, 3 and the load caused by a uniform line load, r_u, should be used to check the frame mullions and fasteners for compliance with the deflection and stress criteria stated above. It is important to note that the design load for mullions is twice the load given by Equations 1 to 3, in order to account for effects of two panes being supported by a common mullion.

x: Distance from corner measured along long edge of glass pane

Table 6: Coefficient for Frame Loading

a/b	C_R	C_x	C_y
1.00	0.065	0.495	0.495
1.10	0.070	0.516	0.516
1.20	0.074	0.535	0.533
1.30	0.079	0.554	0.551
1.40	0.083	0.570	0.562
1.50	0.085	0.581	0.574
1.60	0.086	0.590	0.583
1.70	0.088	0.600	0.591
1.80	0.090	0.609	0.600
1.90	0.091	0.616	0.607
2.00	0.092	0.623	0.614

- ***Recommendation***

In the case of PVC widow framing it is essential to note that the Tensile strength of PVC used for this application is 13.798 MPa. The flexural strength is 72.39 MPa.

PVC frame is extruded to engulf the steel skeleton. On the other hand Eco-Board has to be assembled of 4 cut surfaces in order to engulf the skeleton. The surfaces are joined together by an adhesive. This threatens the integrity of the system since Eco-Board systems joined by adhesives have not been tested for their integrity yet.

Thus it is recommended not to use Eco-Board for this application.

D. Concrete Formwork

A prospective use of Eco-Board is to replace timber (plywood and OSB) in the sheathing of concrete formwork. To do this we must first specify the design criteria and properties to achieve proper use of the form work. Second we compare the relevant properties of Eco-board to those of timber.

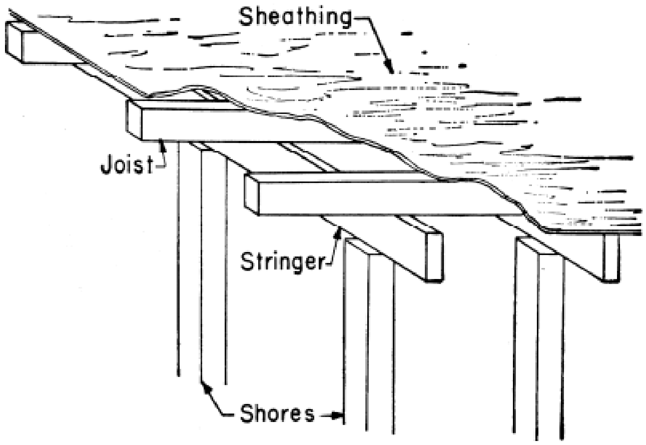
The changes in sheathing material only affect the number of joists used. Thus we calculated the costs of the sheathing material and the costs of the joist, both per meter squared.

It is important to state that the number of times a sheathing board is reused is affected by the water absorption of the board itself. Wood is affected by moisture content higher than about 19%. Higher moisture content significantly softens the wood fibers and makes it less stiff and less able to carry stresses(Alexander, 2003). Concrete's moisture level gradually drops from an initial 60% to below 20% after 7 days of pouring(Drying of Concrete , 2013). This forces the use of marine treated boards if reuse is required. Also in the case of large boards used as sheathing there are no fasteners used to hold the boards to the joists, which means that serious loss of board life occurs when they are dropped on corners or edges. This means that the stripping (removal process) is important(Halvorsen, 1993). So if the work force is skilled the damage from assembly and removal of the formwork is minimal. When disregarding water induced damage t was found that the three factors had impact on the reuse of timber formwork : working attitudes of workmen, efficiency of workmen and formwork stripping process(Y.Y. Ling, 2000).

In our study we took into account the number of times each type of board could be used and the number of times a joist could be used. We found out he possible number of times used for the wooden boards by surveying several contractors in the Lebanese market asking them about the type, brand and the number of times they have re-used a board.

We have also estimated the number of times an Eco-Board could be reused. We waterproof, using a polyurethane based product, the edges, which are the only point of water absorption in Eco-board, as both surfaces of Eco-Board are laminated. We have estimated the times of use of Eco-Board a sheathing to be 10 times based on the fact that when the edges are sealed there is no water absorption, and damage only be inflicted by mishandling while assembling the sheathing or removing it or during moving it. This is because polyethylene based products fail under low stress only in the case of the presence of notches and cracks inflicted by mishandling (including polyethylene water pipes), and the only time water plays a role in this failure is when the an electrical field is in direct vicinity, as the case of water trees formed in the cracks of electrical insulation material made of polyethylene(Peacock, 2000)

The equations used in this section are all corroborated in "Concrete Formwork Systems" a book by Awad S. Hanna (Hanna, 1998)



(Lyngcoln, 1993)

1. DESIGN LOADS:

1.1. Vertical Loads

Design load for formwork are the dead load plus live load per square meter of form contact area. The dead load is defined as the weight of the reinforced concrete plus the weight of the formwork. The live load is defined as additional loads imposed during the process of construction such as material storage, personnel and equipment.

Formwork impact load is a resulting load from dumping of concrete or the starting and stopping of construction equipment on the formwork. An impact load may be several times a design load.

1.2. Dead load

The dead load is that of the concrete and rebar, embedment and formworks.

Concrete and Rebar have a density ranging from 2.08 to 2.56 Tons/m^3. For the sake of our analysis we took the maximum density. We assumed a 20 cm thick slab.

Embedment and Formworks results in a load of 48.2 Kg/m^2 which equals 0.478 KPa

The dead load total is the summation at 5.4 KPa.

1.3. Minimum construction live load

The minimum construction live load is taken to be that of the personnel, equipment, mounting of concrete and impacts.

It is usually estimated at 2.4 KPa (3.6 KPa if carts are used). We assumed no carts used.

1.4. Total form design load

The total form design load is at 7.8 KPa.

2. SHEATHING DESIGN

In the sheathing design we considered and analyzed the distance between joists supporting the sheathing.

Since forms have continuity in their use we did not attempt to change the base design values for load.

2.1. BENDING Restrictions

We considered the Eco board with 2 cm thickness and 1 m in width. The goal is to find the maximum allowable distance, l, between joists.

$$l=10.95\sqrt{F * S/w}$$

This equation is derived from the equation of the maximum allowable moment of a continuous beam.

$$M_{max}=\frac{Wl^2}{120}$$

F being the bending strength of the material. S is the effective section modulus of the geometric shape of the beam and w is the total load applied.

2.2. DEFLECTION Restrictions

For determining the maximum allowable distance between joists for deflection, we should first specify the allowable deflection. It is preferred to assume maximum allowable deflection at 1/16 of an inch or 15 mm. This was done using the following equation:

$$l=3.23\sqrt[4]{E*I/w}$$

This equation is derived from the maximum deflection equation.

$$\Delta_{max} = \frac{1}{145} \times w \times \frac{l^4}{EI}$$

E being the modulus of elasticity and I being the moment of inertia.

2.3. ROLLING SHEAR Restrictions

For determining the maximum allowable distance between joists for rolling shear we used the following equation:

$$l=\frac{F}{0.6w}*\frac{I*b}{Q}$$

This equation is derived from the shear equation

$$F_S = \frac{V_{Max}Q}{bI} \text{ and } V_{Max} = 0.6wL \Rightarrow F_S = 0.6wL\frac{Q}{bI} \text{ or}$$

$$L = \frac{F_S}{0.6w} \times \frac{Ib}{Q}$$

F being the shear strength, w the load, I the moment of inertia, b the width of the element and Q the first moment of area of the particular geometrical shape.

3. *Joint Size and Spacing of Stringers to Support the Joists*

We chose to use a 2 by 4 construction grade beam as a Joist. This beam has an extreme bending strength of 6.89 MPa, a shear strength of 0.655 MPa and a Modulus of Elasticity of 10.34 GPa.

We calculated the uniformly distributed load on the joist w' = L*w. Where L is the maximum allowable joist distance and w is the total design uniformly distributed load.

3.1. BENDING Restrictions

The goal is to find the maximum allowable distance, l, between stringers.

$$l=10.95\sqrt{F * S/w'}$$

F being the bending strength of the material. S is the effective section modulus of the geometric shape of the beam and w' is the total load applied.

3.2. DEFLECTION Restrictions

For determining the maximum allowable distance between stringers for deflection, we should first specify the allowable deflection. It is preferred to assume maximum allowable deflection at 1/16 of an inch or 15 mm. This was done using the following equation:

$$l=3.23\sqrt[4]{E * I/w}'$$

E being the modulus of elasticity and I being the moment of inertia.

3.3. Shear Restrictions

For determining the maximum allowable distance between stringers for shear, we should solve for L using:

$$F=\left(\frac{0.9w'}{bd}\right)(L-2d)$$

Where F is the shear strength of the material, b is the width of the cross section of the beam and d is the length of the cross section of the beam .

4. Stringer Size and Shore Spacing

We calculated the uniform on the stringer to be w''=L*w where L is the maximum allowable spacing between stringers.

We chose to use a 3 by 6 construction grade beam as a Stringer. This beam has an extreme bending strength of 6.89 MPa, a shear strength of 0.655 MPa and a Modulus of Elasticity of 10.34 GPa.

4.1. BENDING Restrictions

The goal is to find the maximum allowable distance, l, between shores.

$$l=10.95\sqrt{F*S/w''}$$

F being the bending strength of the material. S is the effective section modulus of the geometric shape of the beam and w' is the total load applied.

4.2. DEFLECTION Restrictions

For determining the maximum allowable distance between shores for deflection, we should first specify the allowable deflection. It is preferred to assume maximum allowable deflection at 1/16 of an inch or 15 mm. This was done using the following equation:

l=$3.23\sqrt[4]{E * I/w}''$

E being the modulus of elasticity and I being the moment of inertia.

4.3. Shear Restrictions

For determining the maximum allowable distance between shores for shear, we should solve for L using:

F=$\left(\frac{0.9w'}{bd}\right)(L-2d)$

Where F is the shear strength of the material, b is the width of the cross section of the beam and d is the length of the cross section of the beam .

5. Plywood Formwork

The same equations and restrictions are applied to plywood boards of 3/4" and 8 ft wide. Plywood boards of these dimensions have a bending strength of 10.65 MPa, a shear strength of 0.39 MPa and a modulus of elasticity of 10340 MPa.

The bending restriction results in a maximum joist distance of 3.4m.

The deflection restriction (at a maximum deflection of 1/16") results in a joist distance of 0.69m.

The rolling shear restriction results in a maximum joist distance of 0.58m.

The ruling maximum distance between joists is that of the rolling shear, standing at 0.58m.

The ruling maximum distance between stringers is that of the bending restriction at 0.89m.

The ruling maximum distance between shores is that of the bending restriction at 1.6m.

6. Oriented Strand Board Formwork

We applied the same equations for Oriented Strand Board with thickness of 0.22 m and width of 1.22m. Oriented strand board of these dimensions have a bending strength of 30 MPa, a shear strength of 0.3 MPa and a modulus of elasticity of 5700 MPa (Manuel Rebollar, 2007).

The bending restriction results in a maximum joist distance of 6.7m.

The deflection restriction (at a maximum deflection of 1/16") results in a joist distance of 0.62m.

The rolling shear restriction results in a maximum joist distance of 0.47m.

The ruling maximum distance is that of the rolling shear, standing at 0.47m

The ruling maximum distance between stringers is that of the bending restriction at 1m.

The ruling maximum distance between shores is that of the bending restriction at 1.54m

7. Eco-Board Formwork

Knowing that F for eco-board is 1.28 MPa, we get a maximum allowable distance between joists of 1.14m.

Knowing that the modulus of elasticity of Eco-board is208 MPa, maximum allowable distance for deflection is 0.29m

Knowing that the shear strength of Eco-board is 1.9 MPa, the maximum allowable distance between joists was found to be 3.38m.

The ruling "l" is the smallest distance allowed for the 3 aforementioned restrictions, which is 0.29m in our case.

The ruling maximum distance between stringers is that of the bending restriction at 1.25m.

The ruling maximum distance between shores is that of the bending restriction at 1.377m

8. Costs and Recommendations

Using marine treated Plywood, 1 m^2 of sheathing costs 24.7\$/m^2 of plywood board in addition to cost of 1.7- 1 m long joists/m^2 at 13.5\$/m length of joists, 1.11- 1m long stringers/m^2 at 15\$/m length of stringers and 0.6- 3m long shores at 14\$/m. A marine treated plywood board of the highest quality has been found to be used 7 times before deterioration. The water marine treating of plywood takes place during manufacturing through the use of phenolic- resin - impregnated coating which deteriorates gradually as the board is used(Halvorsen, 1993). This means the cost is 3.52\$/m^2. The joists, stringers and shores are usually used for 50 times so this puts the cost at 1.31 \$/m^2. The total cost for using a plywood board is 4.84 \$/m^2.

Using Oriented Strand Board, 1 m^2 of sheathing costs 13.21$/$m^2$ of OSB board in addition to cost of 2.12- 1 m long joists/m^2, 1- 1m long stringers/m^2 at 15$/m length of stringers and 0.64- 3m long shores at 14$/m. OSB has been found to be used for 2 times. Given the same parameters for the joists, stringers and shores the total price of using OSB 8.07 $/$m^2$.

Using Eco-board, 1 m^2 of sheathing costs 25$/$m^2$ of Eco-board in addition to cost of 3.34- 1 m long joists/m^2 used 50 times each, 0.79- 1m long stringers/m^2 at 15$/m length of stringers and 0.72- 3m long shores at 14$/m. Also a board is sold for recycling for 1/4 of its original price. Also we waterproof, using a polyurethane based product, the edges, which are the only point of water absorption in Eco-board, as the both surfaces of Eco-Board are laminated. We have estimated the times of use of Eco-Board a sheathing to be 10 times based on the fact that when the edges are sealed there is no water absorption. The total costs stand at 4.74 $/$m^2$.

Table 7: Comparison of Sheathing Material

Sheathing Material	***Cost $/$m^2$***
Plywood- Marine Treated	4.84
OSB	8.07
Eco-Board-Water Proofed	4.74

It is recommended to use Eco-Board given that it is cheaper. To further confirm this recommendation it is important to test Eco-Board as sheathing to validate the exact number of times it could be used. It may be found that the initial estimate is low, and the actual number of times of reuse could be larger, especially if the boards are it is used it in a formwork system which is moved without as a unit without dismantling. If dismantling is required, the use and re-use of fasteners in Eco-Board might lower the lifetime. Other factors that need to be better understood include the effects of using fasteners on Eco-Board over extended periods, and the effects of the stresses of taking the forms off the concrete after it sets.

E. *Exterior Wall Systems*

The exterior walls system is usually made of concrete masonry unit (CMU). The blocks are either 15 cm thick and one layer or double walls built with 10 cm thick blocks.

The exterior walls system was investigated as follows: single wall CMU and double wall CMU, with the former divided into two categories (single 15 cm wall and single 10 cm wall with double Eco-board panel) and the latter divided into three categories differing in the components of the middle section of the configuration (either air gap or Styrofoam or double Eco-board panel).

For this use eco-board has to be painted and fire proofed in the first category. The configurations differ not only in cost but also in thermal efficiency.

The comparison was set on the base of the cost of wall in $/m^2, and thermal conductivity of each configuration.

The thermal conductivity of 15 cm CMU is K_{15CMU}=0.377 W/m^{2}K , that of 10cm CMU K_{10CMU}= 0.42 W/m^{2}K, that of Eco-Board is K_E=0.307 W/m^{2}K, that of the aforementioned double Eco-Board K_{dE}=0.04 W/m^{2}K, that of Styrofoam K_s= 0.05 W/m^{2}K, and that of air K_A= 0.026 W/m^{2}K.

The thermal conductivities of the configurations were calculated using lumped capacity method.

The thermal conductivities of both the 15 and 10 cm CMU was tested for at the Heat Transfer Lab at AUB.

- ***Single Wall Concrete Masonry Unit***

  - ***Single 15-cm CMU***

The costs of this configuration are those of the CMU, its building, plastering and painting (from the inside). The cost of the block and its building is 6.25 $/m^2 and that of plastering and painting is 21.5 \$/m^2. The total cost is 27.75 \$/m^2. The thermal conductivity of this system is 0.377 W/m^{2}K.

- ***Single 10-cm CMU and Double Eco-Board Panel***

The costs of this configuration are those of the CMU, its building, double Eco-Board panel (which has a 2cm Styrofoam panel in between) and the cost of painting and fireproofing it. The cost of the block and its building is 4.125 \$/m^2, that of Eco-board is 52.1 \$/m^2 and that of painting and fireproofing is 3.82 \$/m^2 combined. The total cost is 60 \$/m^2. The thermal conductivity of this system is 0.034 W/m^{2}K

- ***Double Wall Concrete Masonry Unit***

- ***Air Gap***

The costs of this configuration are those of the 10 cm CMU (both walls are built with it), its building, plastering and painting (from the inside). The cost of the block and its building is 8.25 \$/m^2 and that of plastering and painting is 21.5 \$/m^2. The total cost is 29.75 \$/m^2.The thermal conductivity of this system is 0.023 W/m^{2}K.

- ***Styrofoam Panel***

The costs of this configuration are the same to the double wall with air gap but with the addition of the cost of a 5cm thick Styrofoam panel. The Styrofoam panel costs 7.25 \$/m^2. The total cost is 37 \$/m^2. The thermal conductivity of this system is 0.04 W/m^{2}K.

- ***Double Eco-Board Panel***

The costs of this configuration are the same to the double wall with air gap but this time with the addition of the cost of the double Eco-board panel (which also has a 2cm thick Styrofoam panel in between). The double Eco-board panel costs 52.1 \$/m^2. The total cost is 81.85 \$/m^2. The thermal conductivity of this system is 0.032 W/m^{2}K

Table 8: Comparison of Exterior Wall Systems

Wall Configuration	***Cost $/m²***	***Thermal Conductivity W/m²K***
Single 15 cm	27.75	0.377
Single 10 cm & double Eco-Board	60.045	0.034657907
Double 10 cm & Air gap	29.75	0.023135593
Double 10 cm& Styrofoam board	37	0.040384615
Double 10 cm& double Eco-Board	81.85	0.032015986

If thermal insulation is not a priority then a single 15 cm wall is recommended. If thermal insulation is a priority then, Double 10 cm & Air gap is recommended as it has the lowest thermal conductivity and is the cheapest of all configurations having thermal conductivities in its conductivity's vicinity. Even if there is a fear of water leakage or humidity in the air gap, thus molding, using Double 10 cm& Styrofoam board is still preferred to any configuration containing Eco-Board as the difference in thermal conductivity is negligible, while that in the cost is large.

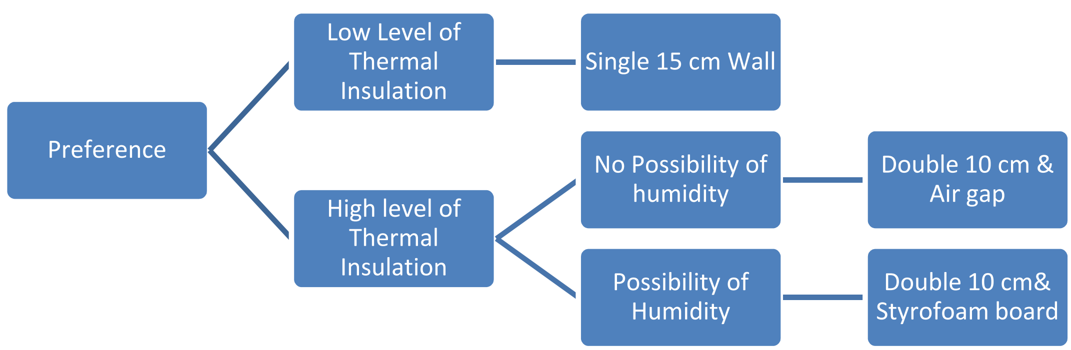


Figure 12: Exterior Wall System Preference Tree

CHAPTER VI

CONCLUSION AND FUTURE WORK

1. Supply of Raw Material and National Policy Effect

The producing company of Eco-board is supplied currently by a recycling plant which it owns. This plant services two small towns south of Lebanon which have an estimated permanent resident population of 10000 people. These towns are dependent on farming as their main economic income. This plant supplies an average of 1.42 tons/day of shredded low density polyethylene. This amount is enough to produce 42 board (2m-1m-0.02m).

Although there is a considerable number of recycling facilities in Lebanon, there are no reported statistics on the actual amount of recycled materials and their types. The Ministry of Environment in Lebanon reports the presence of 8 recycling plants which transform low density polyethylene, and 2 collectors. Of these 10 facilities only 4 offer transportation to and from sites(Management of Recyclable Material, 2011) .

The lack of documented statistics doesn't allow us to clearly evaluate the supply of raw materials for the manufacturing of Eco-Board. On the other hand the statistics offered by the manufacturing company through their own sorting plant gives us a glimpse of the potential of raw materials supply, especially that the towns which this plant services are of agricultural nature, which implies that more urban locations provide more tons/capita.

A national policy easing and encouraging the collection and transformation of plastic waste, especially low density polyethylene, could make the production of Eco-Board a more attractive industrial sector, both economically and logistically.

Another route which could encourage this process is a set of policies which helps introduce the use of Eco-Board into the Lebanese construction industry. One possible policy is property tax reduction on housing units using or had used recycled material in the finishing or the construction process. This would make such units more desirable by buyers and consequently by project owners.

Another possible policy is the increase of the "Exploitation Factor" for properties on which projects where recycled material is used. The "Exploitation Factor" is the allowable percentage area of construction from the total area of the property. The increase could be relative to the type and amount (by weight) of the recycled materials used.

2. Recommendations

Eco-Board is a versatile material which could fit in different uses in the construction process. Its properties allow it to be used as a replacement of several systems including roofing for mild weather shelter, wall systems, formwork and window framing.

This research effort has provided, in addition to the properties of Eco-Board, the calculations required to qualify it for use in the aforementioned systems. While some of the components intended for replacement proved to be fitting, Eco-Board exceeded the minimum requirements in most of its proposed uses.

The only restriction which was obvious in all uses was the economical one. A 2-2.5 cm thick Eco-Board costs, in the market, 25$/m^2. While this is due to the high prices of plastic in the Lebanese market, whether fresh or recycled, most of the materials we compared it to are cheaper even if higher qualities of the same material might cost more than Eco-Board.

As for the use of roofing component for a mild weather shelter, the recommendation was to use Eco-Board as it is a cheaper option than steel.

For partition walls, it was recommended to use a single layer of Eco-Board because its strength is well above that of alternatives, and as its thermal conductivity is almost the same as a double layer, while costing considerably less.

The low prices of gypsum board proved Eco-Board economically unusable as a partition wall or false ceiling. Eco-Board is not only more costly, but it also has a higher thermal conductivity of compared to Gypsum Board. Also, in the case of gypsum-based false ceilings, Eco-Board is much less versatile as a substitute because the difficulty of using fasteners on it meant that it could only be used in a wall-to-wall segments of the ceiling..

As for the external wall systems, it is obvious that Eco-Board is not recommended in any of the cases or preferences, as the cost of including it in a configuration is too high for its advantage in thermal conductivity on other configurations.

When used as sheathing material in concrete formwork, Eco-Board's reusability proved vital in having a lower cost than other sheathing material.

Eco-Board was not recommended in the window framing system due to structural concerns, arising from the assembly method of Eco-board as a frame.

3. Future Work

For future work, the priority should be given to using Eco-Board as sheathing to confirm the exact number of times it could be used. Our initial estimation is probably on the conservative side, so the actual number of times of reuse could be larger. Also it would be important to use it in a formwork system which is moved without taking apart, which would require the use of fasteners in Eco-Board. This type of use would help us understand Eco-Board's behavior when it is fastened for a long time.

Also it is important to study the toxicity of Eco-Board. This could be done by designing a set of tests for known toxins and carcinogens.

Another important aspect is to study the durability of paint on Eco-Board, especially in various weather conditions. This is especially important for the use of Eco-board as a roofing material.

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Appendix 1: Testing Standards

ASTM D570:

1. Scope: This test method covers the determination of the relative rate of absorption of water by plastics when immersed. This test method is intended to apply to the testing of all types of plastics, including cast, hot-molded, and cold-molded resinous products, and both homogeneous and laminated plastics in rod and tube form and in sheets 0.13 mm (0.005 in.) or greater in thickness.
2. Significance and use:
    a. This test method for rate of water absorption has a chief function, as a guide to the proportion of water absorbed by a material.
    b. Comparison of water absorption values of various plastics can be made
3. Apparatus:
    a. *Balance*—An analytical balance capable of reading 0.0001 g.
    b. *Oven,* capable of maintaining uniform temperatures of 50 ± 3°C (122 ± 5.4°F) and of 105 to 110°C (221 to 230°F).
4. Test Specimen: The test specimen for sheets was in the form of a bar 76.2 mm (3 in.) long by 25.4 mm (1 in.) wide by the thickness of the material.

ASTM E1269:

1. Scope: This test method covers the determination of specific heat capacity by differential scanning calorimetry. The normal operating range of the test is from –100 to 600 °C. Computer or electronic-based instrumentation, techniques, or data treatment equivalent to this test method may be used.
2. Significance and use: Differential scanning calorimetric measurements provide a rapid, simple method for determining specific heat capacities of materials.

3. Apparatus:
    a. *Temperature Sensor,* to provide an indication of the specimen temperature to ± 10 mK (0.01 °C).
    b. *Differential Sensor,* to detect heat flow difference between the specimen and reference equivalent to 1 µW.
4. Test Specimen: No specified dimensions or shape.

ASTM E1530:

1. Scope: This test method covers a steady-state technique for the determination of the resistance to thermal transmission (thermal resistance) of materials of thicknesses less than 25 mm. This test method is useful for specimens having a thermal resistance in the range from 10 to 400 × 10^{-4} $m^{2}\cdot K\cdot W^{-1}$, which can be obtained from materials of thermal conductivity in the approximate range from 0.1 to 30 $W\cdot m^{-1}\cdot K^{-1}$ over the approximate temperature range from 150 to 600 K.
2. Significance and use: This test method is designed to measure and compare thermal properties of materials under controlled conditions and their ability to maintain required thermal conductance levels.
3. Apparatus: Hot/Cold plate
4. Test Specimen: 30-30-2.5 cm sheet.

ASTM D2344/D2344M:

1. Scope: This test method covers the determination of the mechanical properties of unreinforced and reinforced rigid plastics, including high-modulus composites, when loaded in compression at relatively low uniform rates of straining or loading. This procedure is applicable for a composite modulus up to and including 41,370 MPa (6,000,000 psi).
2. Significance and use:

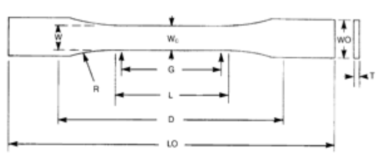
Flexural properties tested for by these test methods are used for quality control and specification purposes

3. Apparatus:
    a. "Testing Machine: A properly calibrated testing machine which can operate at constant rates of crosshead motion over the indicated range, and in which the error in the load measuring system shall not exceed ±1% of the maximum load expected to be measured. It shall be equipped with a deflection measuring device. The stiffness of the testing machine shall be such that the total elastic deformation of the system does not exceed 1 % of the total deflection of the test specimen during testing, or appropriate corrections shall be made. The load indicating mechanism shall be essentially free from inertial lag at the crosshead rate used."
    b. "Loading Noses and Supports—The loading nose and supports are of cylindrical surfaces. The default radii of the loading nose and supports shall be 5.0 ± 0.1 mm (0.197 ±0.004 in.) unless otherwise specified in an ASTM material specification or as agreed upon between the interested parties"

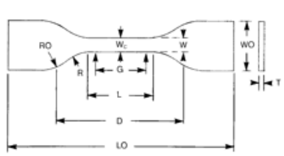
4. "Test Specimen: For materials 2.0 mm or greater in thickness the depth of the specimen shall be the thickness of the material. For all tests, the support span shall be 4 (tolerance ±1) times the depth of the beam. Specimen width shall not exceed one fourth of the support span for specimens greater than 3.2 mm (1⁄8 in.) in depth. Specimens 3.2 mm or less in depth shall be 12.7 mm (1⁄2 in.) in width. The specimen shall be long enough to allow for overhanging on each end of at least 10 % of the support span, but in no case less than 6.4 mm (1⁄4 in.) on each end. Overhang shall be sufficient to prevent the specimen from slipping through the supports."

ASTM D638-10:

1. Scope: This test method covers the determination of the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens when tested under defined conditions of pretreatment, temperature, humidity, and testing machine speed. This test method can be used for testing materials of any thickness up to 14 mm (0.55 in.).
2. Significance and Use:
    a. This test method is designed to produce tensile property data for the control and specification of plastic materials.
    b. Tensile properties may provide useful data for plastics engineering design purposes. However, because of the high degree of sensitivity exhibited by many plastics to rate of straining and environmental conditions, data obtained by this test method cannot be considered valid for applications involving load-time scales or environments widely different from those of this test method.
3. Apparatus:
    a. *Testing Machine*—A testing machine of the constant-rate-of-crosshead-movement type
    b. *Extension Indicator* (extensometer) —A suitable instrument shall be used for determining the distance between two designated points within the gage length of the test specimen as the specimen is stretched.
4. Test Specimen:



TYPES I, II, III & V



TYPE IV

ASTM E84:

1. Scope: This fire-test-response standard for the comparative surface burning behavior of building materials is applicable to exposed surfaces such as walls and ceilings.
2. Significance and Use: This fire-test-response standard for the comparative surface burning behavior of building materials is applicable to exposed surfaces such as walls and ceilings. This test method is intended to provide only comparative measurements of surface flame spread and smoke density
3. Apparatus: Fire test chamber and a Furnace.
4. Test Specimen:
    a. Specimens shall be representative of the materials which the test is intended to examine

Appendix 2: Extended Display of Test Results

I. Absorption

Absorption by Weight

%weight increase= $\frac{Wa-Wb}{Wb} * 100$

Where Wb is weight before immersion, and Wa is weight after immersion.

We tested three specimens without sealing

Specimen	1	2	3
Wb (g)	10.4546	12.2557	10.5355
Wa(g)	11.356	13.2442	11.428
Absorption (%weight)	8.622042	8.065635	8.471359
Average Absorption (%weight)	8.343838		

The result was 8.34% increase in weight

We tested three specimens with sealed edges.

Specimen	1	2	3
Wb (g)	200.224	200.571	210.235
Wa(g)	203.982	210.523	213.845
Absorption (%weight)	0.01	0.04	0.01
Average Absorption (%weight)	0.02		

II. Thermal Conductivity

Thermal Resistance:

The Hot/Cold Plate apparatus at AUB labs gives, as a result of the test, after achieving steady state the thermal resistance R of the specimen. The thermal resistance of Eco-Board was found to be 0.016 m^2K/W.

Thermal Conductivity:

Thermal conductivity K=$\frac{L}{R}$, where L is the length of the cross section of the specimen. Our specimen was 5mm.

Thus we found K= 0.309 W/m^2K

III. Bending Strength

Bending Strength

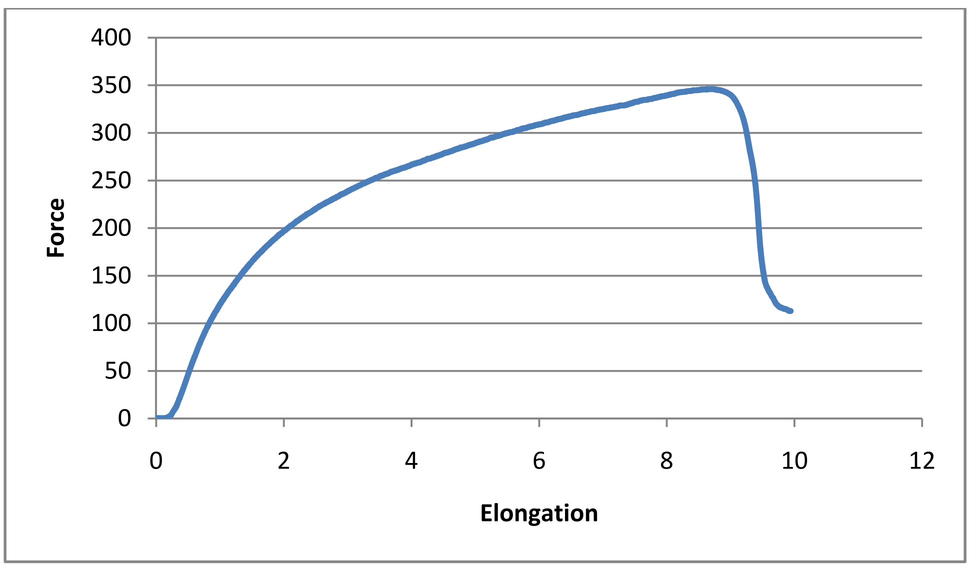
The output of this test was the force applied versus the strain associated with it. We were able to calculate the Stress (Pa) using the following equation

$$\sigma = \frac{0.75F}{A}$$

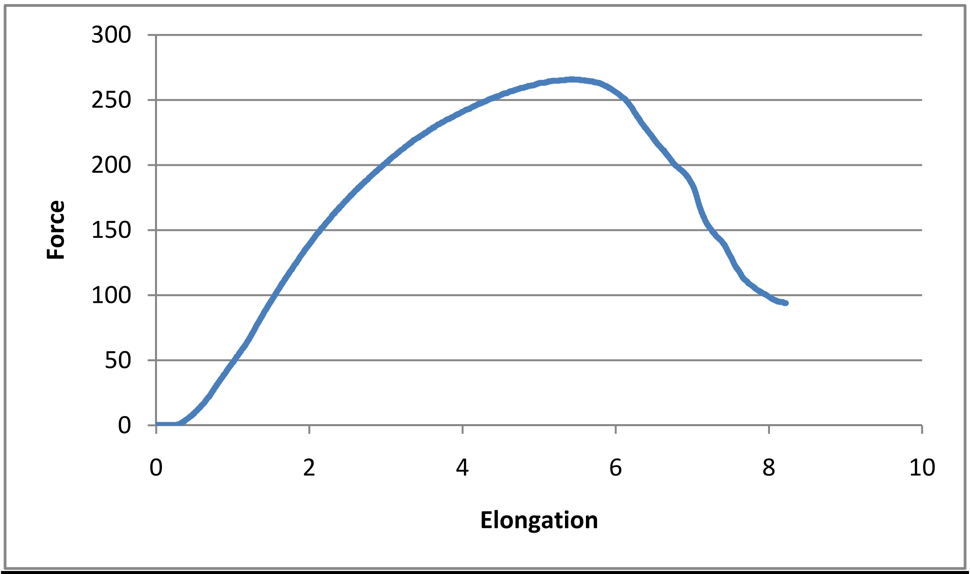
Where σ is the Stress, F is the applied force (at failure) and A is the cross-sectional area of the specimen.

Sample	*Maximum Load N*	*Width mm*	*Thickness mm*	*Strength Mpa*
1	346	18	10	1.441666667
2	266	18	10	1.108333333
3	330.4	19	10	1.304210526
4	223	16	10	1.0453125
5	293.6	15	10	1.468
6	156.6	15	10	0.783
7	256.8	15	10	1.284
8	240	15	10	1.2
9	221.75	15	10	1.10875
10	202.75	15	10	1.01375

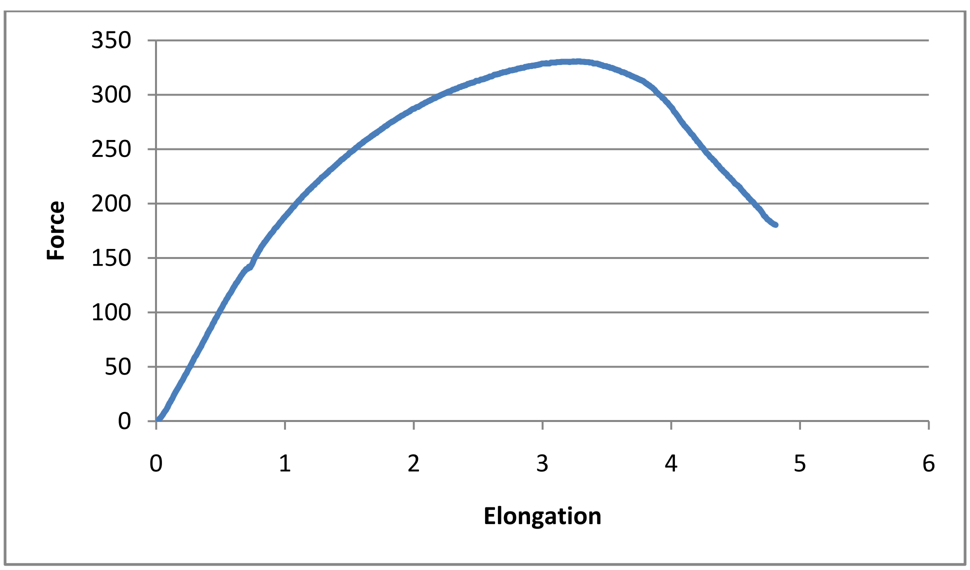
Sample1:Force in N vs. Elongation in mm



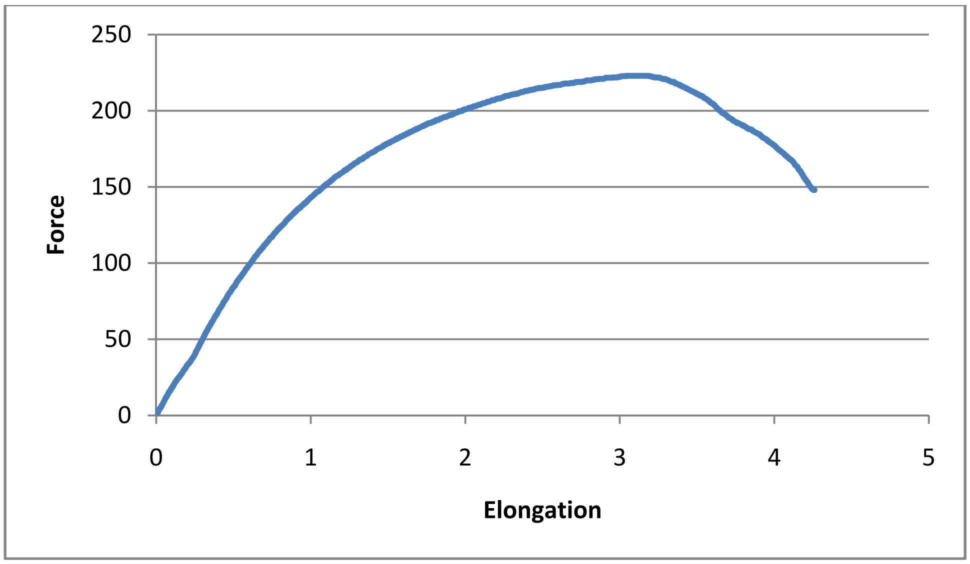
Sample2:Force in N vs. Elongation in mm



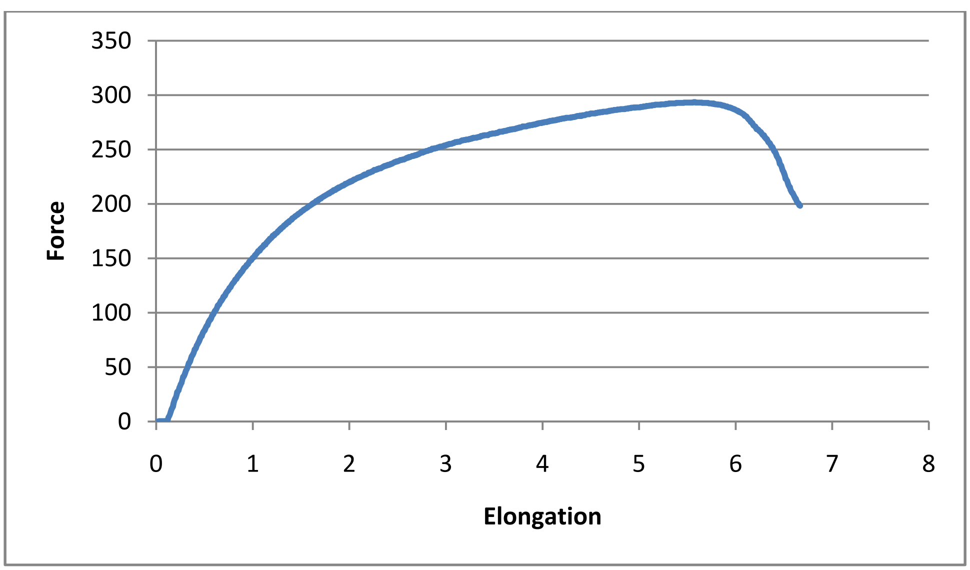
Sample3:Force in N vs. Elongation in mm



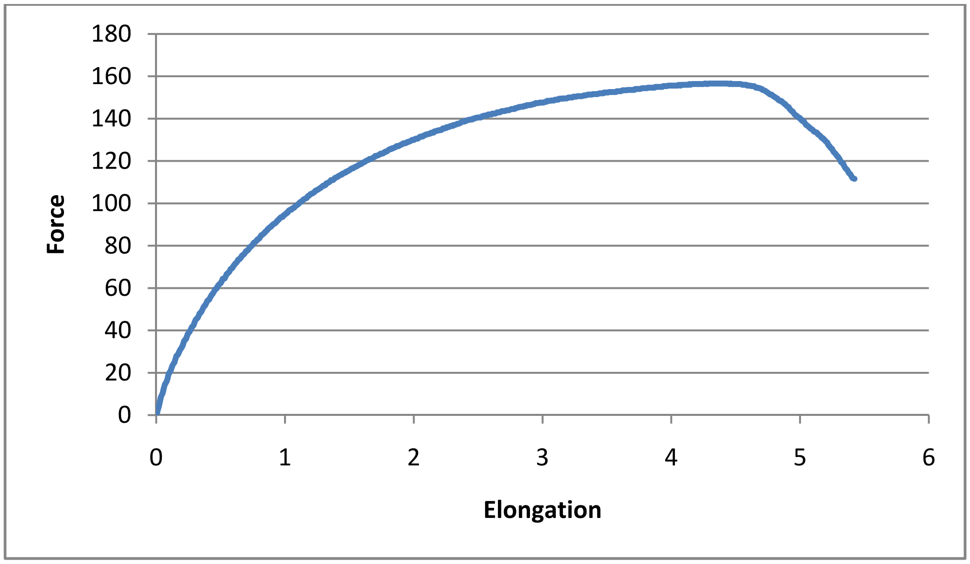
Sample4:Force in N vs. Elongation in mm



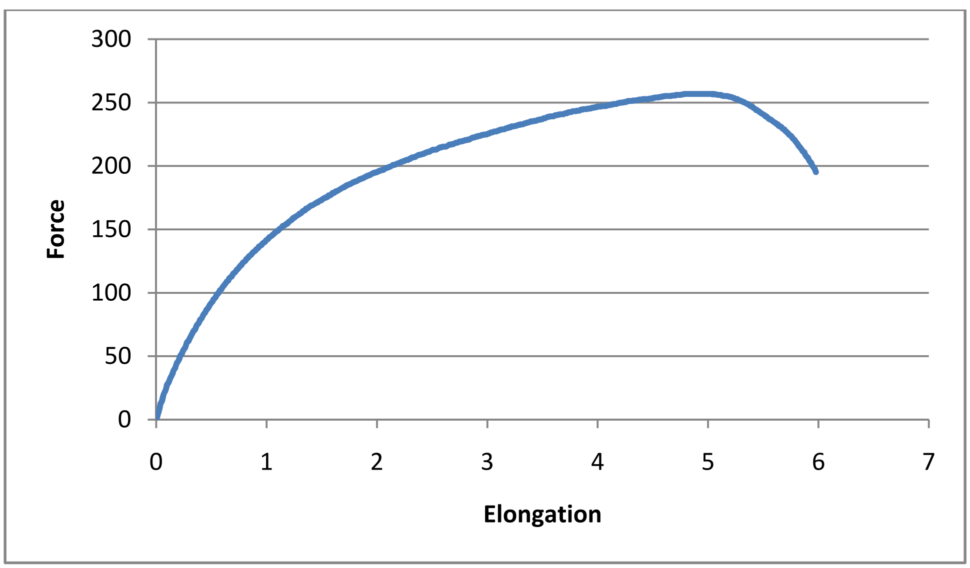
Sample5:Force in N vs. Elongation in mm



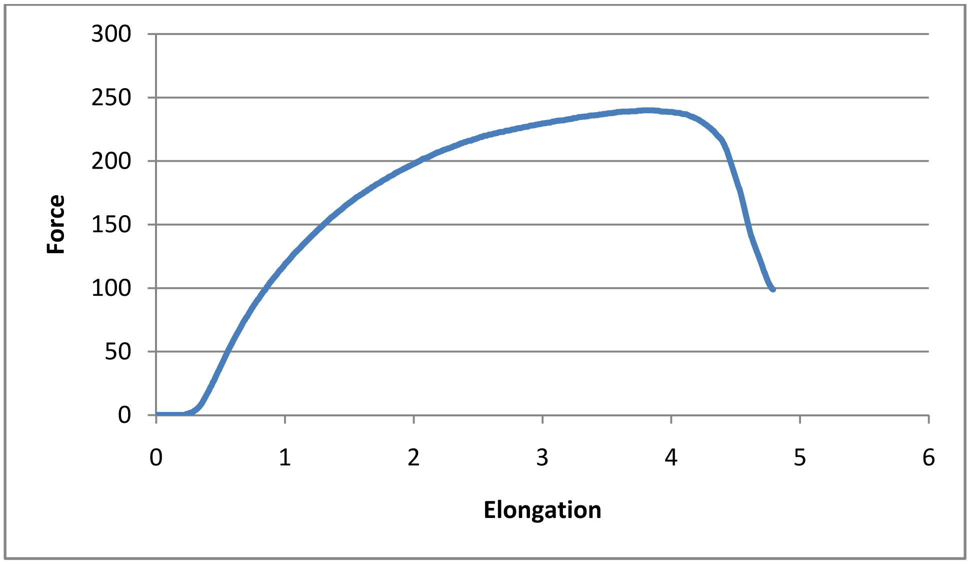
Sample6:Force in N vs. Elongation in mm



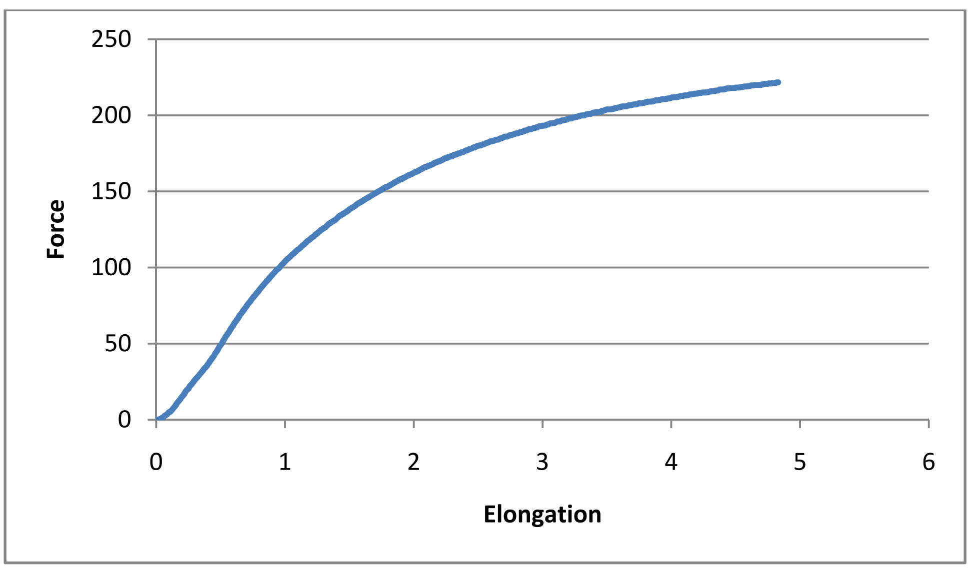
Sample7: Force in N vs. Elongation in mm



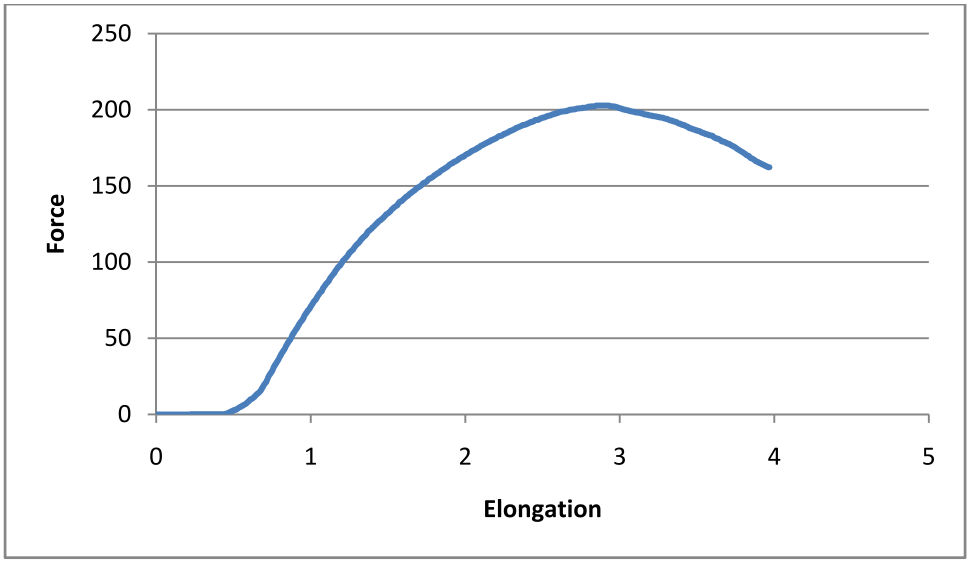
Sample8: Force in N vs. Elongation in mm



Sample9: Force in N vs. Elongation in mm



Sample10: Force in N vs. Elongation in mm



IV. *Tensile Strength*

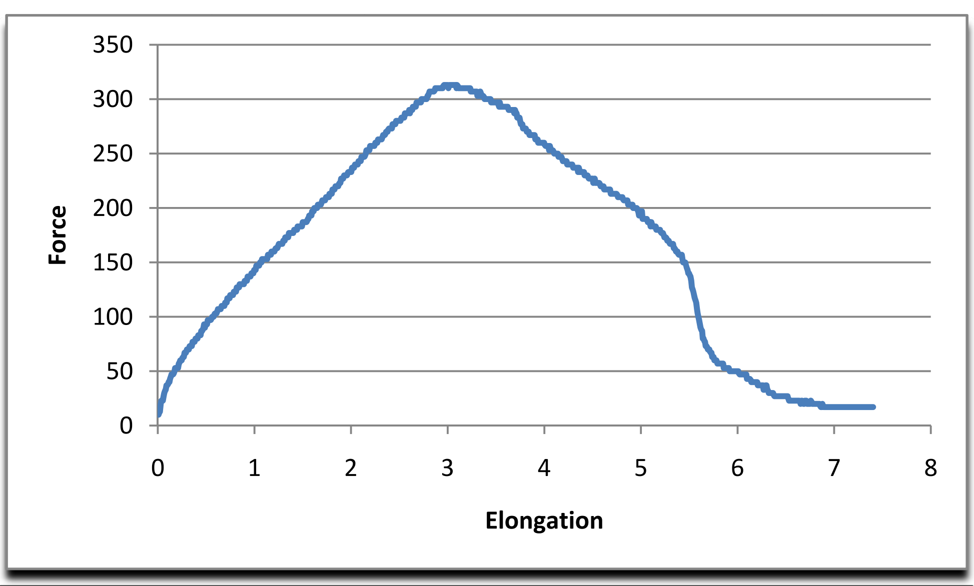
The output of this test was the force applied versus the strain associated with it. We were able to calculate the Stress (Pa) using the following equation

$$\sigma = \frac{F}{A}$$

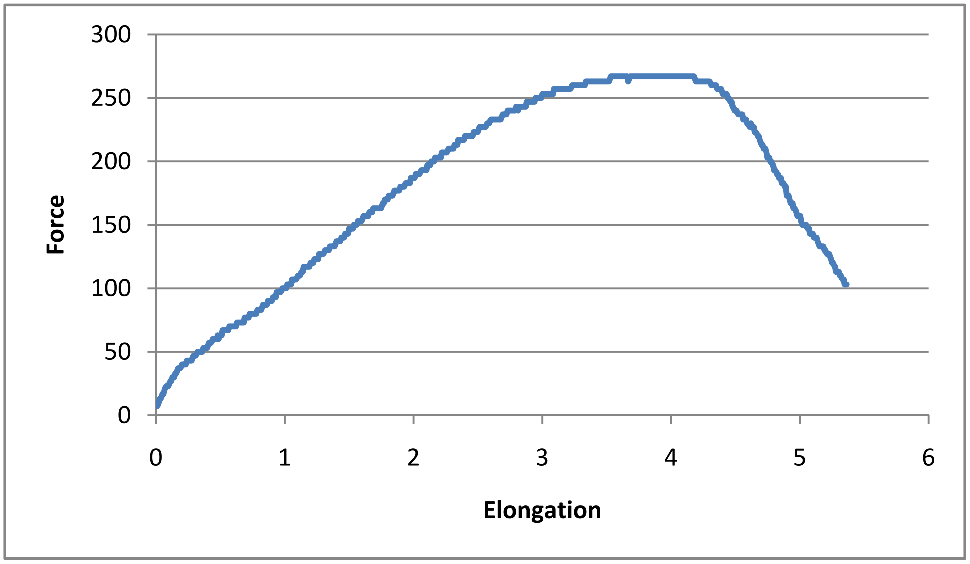
Where σ is the Stress, F is the applied force and A is the cross-sectional area of the specimen

Sample	Maximum Load N	Width mm	Thickness mm	Strength MPa
1	310	8	7	5.5892
2	267	10	7	3.8142
3	270	9	7	4.28571
4	267	10	7	3.7571
5	210	10	7	0.3
6	110	11	7	1.42857
7	310	10	7	4.428
8	203	10	7	2.9
9	310	10	7	4.428
10	267	11	7	3.467

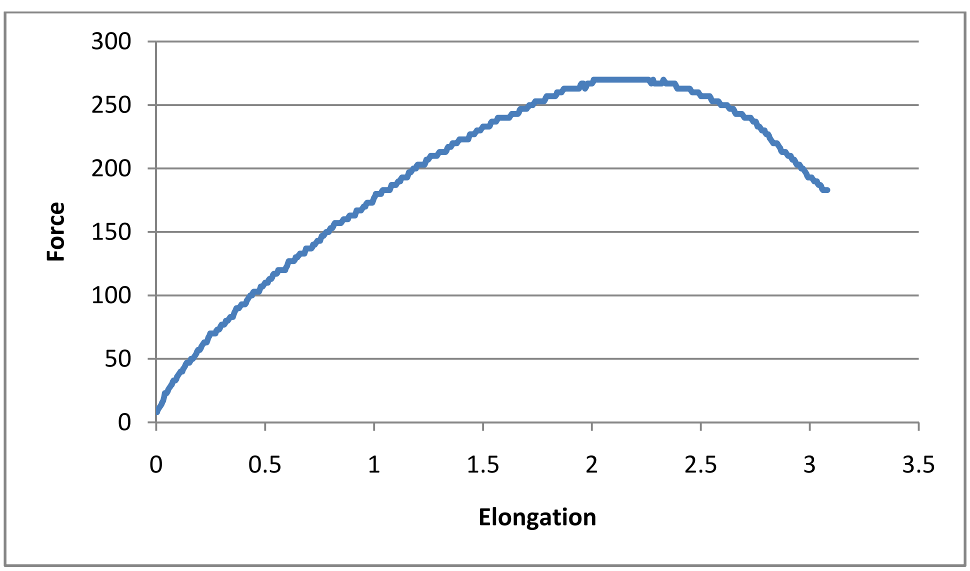
Sample1:Force in N vs. Elongation in mm



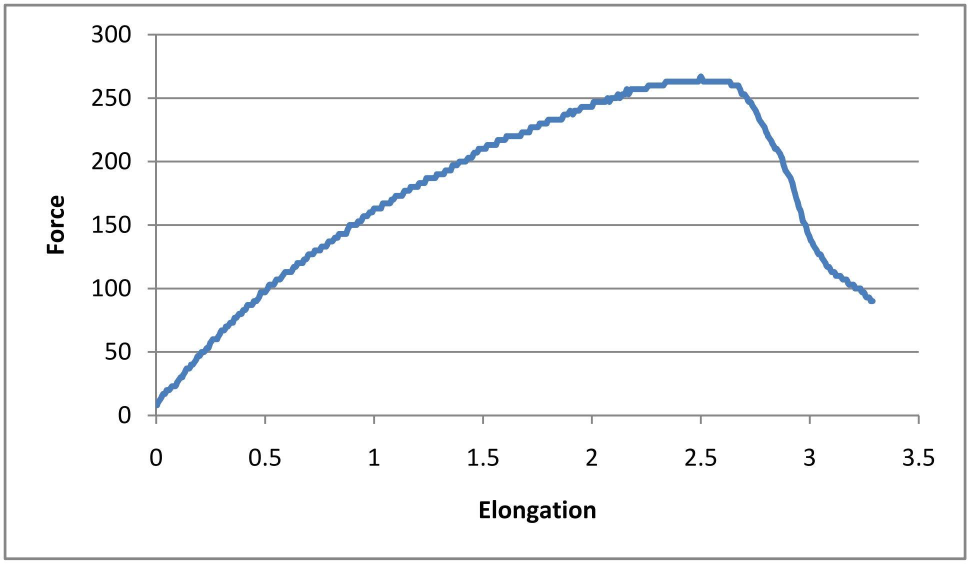
Sample2:Force in N vs. Elongation in mm



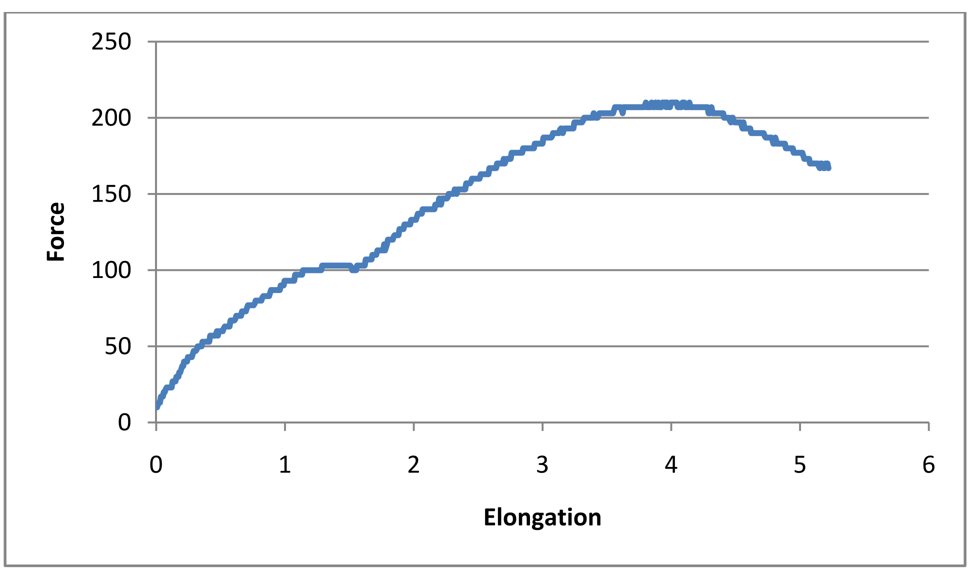
Sample3:Force in N vs. Elongation in mm



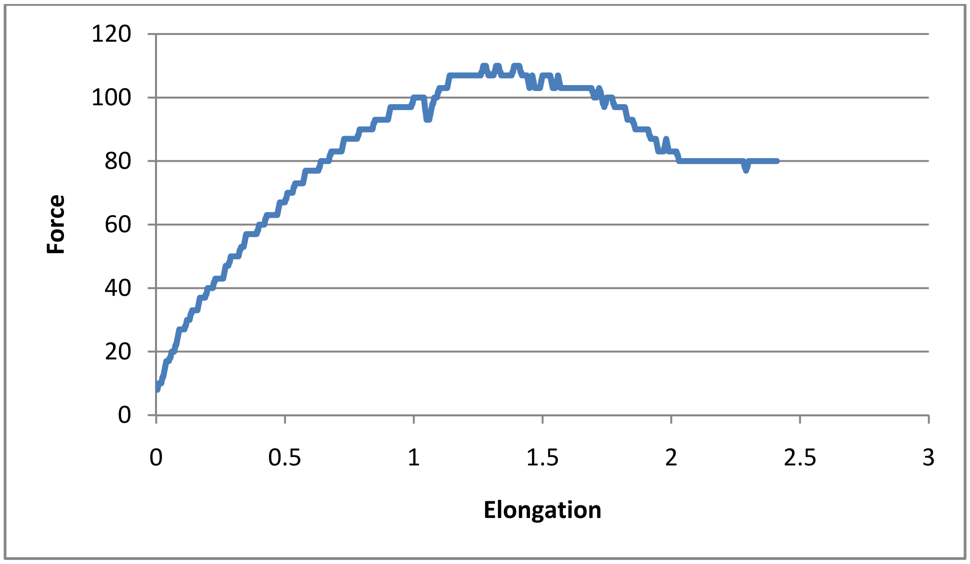
Sample4:Force in N vs. Elongation in mm



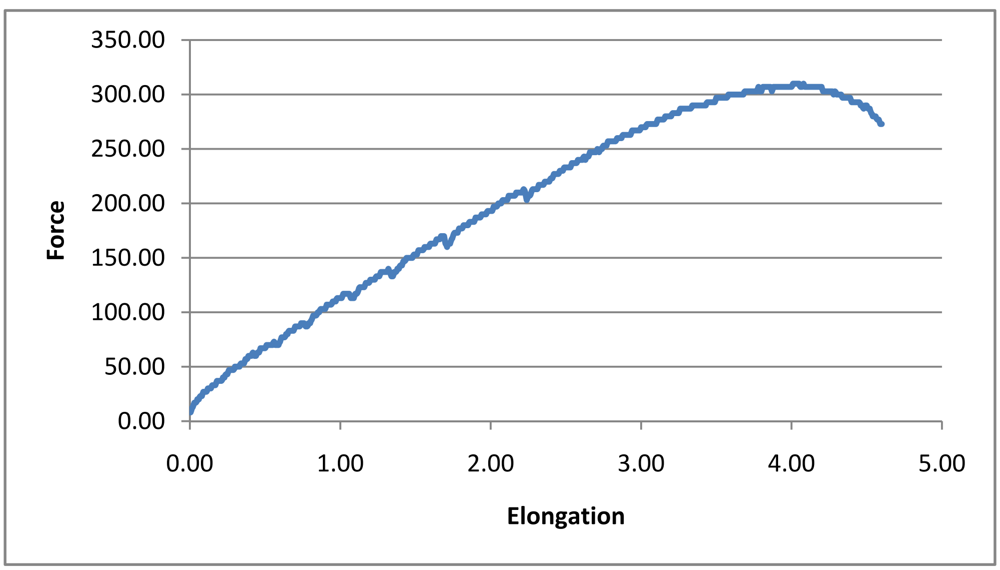
Sample5:Force in N vs. Elongation in mm



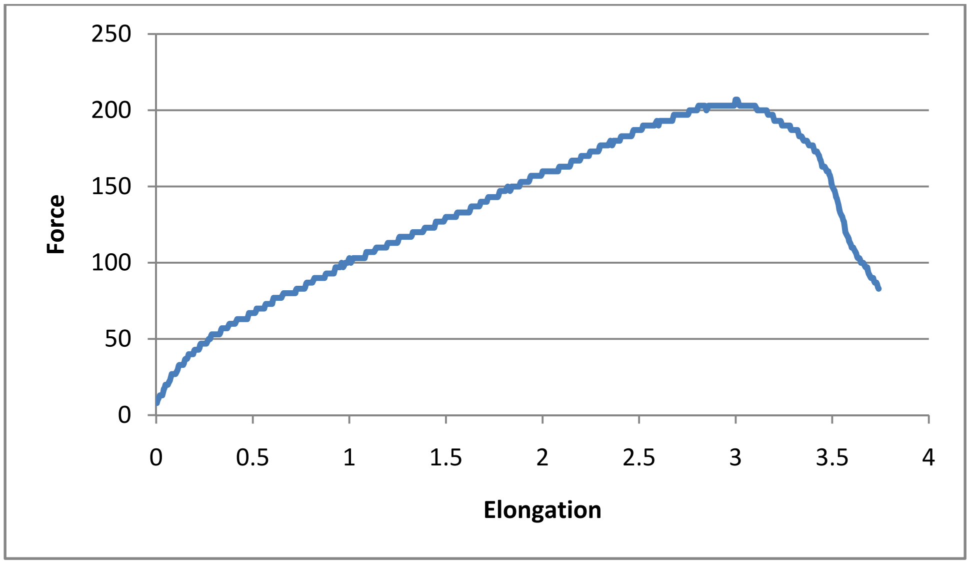
Sample6:Force in N vs. Elongation in mm



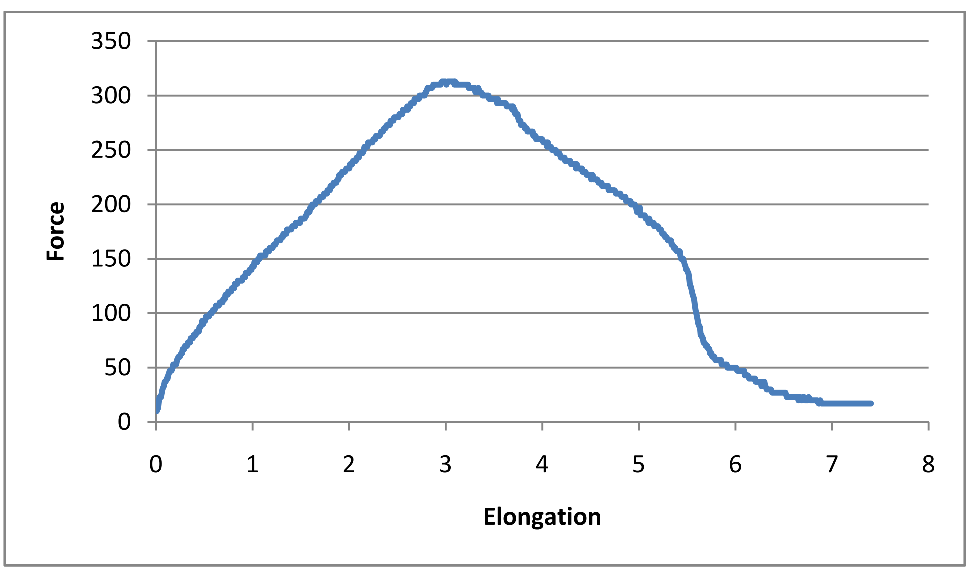
Sample7:Force in N vs. Elongation in mm



Sample8:Force in N vs. Elongation in mm



Sample9:Force in N vs. Elongation in mm



Sample10:Force in N vs. Elongation in mm